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NUTRIENT IMBALANCES OF ASPEN POPLAR IN ACID SULFATE SOILS IN NORTHWESTERN ALBERTA

by

© CHARLES ERNEST BULMER

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING 1987

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled NUTRIENT IMBALANCES OF ASPEN POPLAR IN ACID SULFATE SOILS IN NORTHWESTERN ALBERTA, submitted by CHARLES ERNEST BULMER in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

W. J. Dudas

Supervisor

Kenneth D. Higginbotham

DATE: Dec. 16, 1986

FOR MY MOTHER AND FATHER

ABSTRACT

Release of sulfuric acid during weathering of soil parent materials rich in pyrite results in the development of acid sulfate soils, which occur in both coastal and continental areas. Information is required concerning factors which restrict plant growth in strongly acid soils, whether these soils are naturally occurring or have resulted from deposition of contaminants or exposure of acidic materials during mineral extraction. This study investigated growth disturbances of aspen poplar in a continental acid sulfate soil to provide information on plant - soil interactions in a naturally acidic forest soil.

A catena with extremely unthrifty growth of aspen poplar (Populus tremuloides Michx.)in upper slope positions was selected for study. Soil moisture status, micromorphological features, clay mineralogy and acidity were related to plant growth in this catena. Moisture depletion in the rooting zone in upper slope positions during late summer explained some of the differences observed in tree growth response. Aluminum toxicity aggravated the problem by restricting root access to subsoil moisture.

Plant root development influences structural alterations observed in thin section. Fragmoidic fabric types in the parent materials are transformed, primarily by soil faunal activity into vughy porphyric fabric in the more productive lower slope positions.

The extent of mica depotassification closely relates to the degree of root development as well, with maximum expression of complete depotassification occurring in lower slope positions.

The redistribution of iron released during pyrite and natrojarosite weathering results in high (6.9 %) dithionite-citrate -bicarbonate extractable Fe levels in horizons of accumulationin upper slope positions. Fixation of As, Mo and V contribute to enrichment of these elements in the parent materials and the sola of the catena soils. The soils of the catena are depleted in Br, Ca, Co and Mn.

Despite the extreme acidity and very low nutrient status of these soils, foliar analysis of aspen trees from all sites revealed nutrient concentrations very close to average values reported in the literature. The ability of these plants to exploit soils with very low nutrient levels, and containing high levels of certain phytotoxic elements raises many questions concerning the mechanisms responsible for nutrient uptake and toxin exclusion.

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1. INTRODUCTION

Soil acidity limits plant growth in many areas of the world and under many diverse cropping and production systems. Acid soils develop on parent materials that are low in basic cations or when these cations have been removed by leaching (Foy, 1984). Anthropogenic factors may intensify soil acidity through atmospheric acid deposition and through the use of ammonium fertilizers. Debilitating or insidious growth restrictions are caused by imbalances of nutrients and phytotoxic elements in acidic soil solutions. Research on acid soil - plant systems is aimed at improving productivity in a cost - effective manner. This thesis describes a study of forest - soil interactions in a soil developed on extremely acidic parent material in northwestern Alberta.

Acid sulfate soil conditions develop when soil parent materials rich in pyrite are exposed to an oxidizing environment at the earth's surface. The oxidation of pyrite occurs via several reactions, one of which may be described by:

$$FeS_2 + 15/4\ O_2 + 1/2 H_2O \text{ --->} Fe^{3+} + 2SO_4{}^{2-} + H^+.$$

Extreme soil acidity results if the production of sulfuric acid exceeds the buffering capacity of the soil material.

Acid sulfate soils are distributed worldwide. Dent (1986) estimates that there are 12 million hectares (ha) of potential and actual acid sulfate soils in recent coastal environments. Acid sulfate soils also occur in upland and continental sites (Clark et al, 1961; Clark and Green, 1964; Pawluk, 1971; Buurman et al, 1973; Poelman, 1973; Pawluk and Dudas, 1978; Ivarson et al, 1982; Ross et al, 1982; Wagner et al, 1982; Carson and Dixon, 1983; Mermut et al, 1985; and others). Most studies relating to acid sulfate soils have investigated the processes involved in formation of pyritic sediments and in pyrite weathering and soil genesis. It is now possible to identify potential acid sulfate soils for the purposes of project planning in coastal areas, and to prepare a reasonably accurate assessment of the effects of altering the hydrology in areas susceptible to acidification. Studies relating to plant growth in extremely acidic soils are much less complete, however and further research is required on growth limiting factors present in acid sulfate soils. It is for this purpose that the present study was undertaken.

Observations of an inland acid sulfate soil in northwestern Alberta indicated severely inhibited growth of aspen poplar (*Populus tremuloides* Michx.), and a lack of ground cover species on certain ridge tops. In some areas the ground surface was devoid of vegetation or leaf litter. Morphological deformities of aspen poplar include twisted stems, severe top dieback, bark lesions, and shallow rooting systems. A different response was observed in lower slope positions, where the forest community appeared more productive. The aspen trees in lower slope positions were much larger with straight stems, and no dieback was observed. A diverse cover of herbaceous species and shrubs was observed.

The following two objectives were pursued:

1. to characterize a representative soil catena with the above mentioned vegetative characteristics on the basis of chemical physical and mineralogical properties.
2. to investigate soil conditions implicated in poor growth response of aspen poplar in this catena.

2. ACID SULFATE SOILS IN WESTERN CANADA

2.1 GENESIS OF ACID SULFATE SOILS

The formation of an acid sulfate soil is a two stage process. The initial stage, or reduction stage involves the accumulation of pyrite in coastal depositional environments such as tidal flats and deltaic swamps. The removal of alkalinity produced during the anaerobic decomposition of organic matter results in the development of a potential acid sulfate soil (Pons, 1973). Pyrite is stable in anaerobic environments and the pyritic sediment produced in stage 1 remains unchanged until it is exposed to an oxidizing environment through changes in sea level or drainage. In the presence of oxygen, stage 2 or the oxidation stage occurs, characterized by the decomposition of pyrite leading to the formation of sulfuric acid. Oxidation results in a rapid fall in pH accompanied by the formation of basic ferric sulfates such as jarosite. Soil ripening also occurs as water is removed from the sediment, resulting in consolidation of the soil material and the development of cracks of various sizes allowing improved drainage and aeration. Soil ripening is enhanced by the establishment of deep rooted plant species which are most effective in removal of water from the lower solum. This effect is limited, however by restrictions placed on root development by soil chemical factors. Oxidation may closely follow reduction in coastal areas, due to changes in sea level, or the sediment may remain buried for geologic time spans, resulting in the presence of acid sulfate soils in continental environments.

2.1.1 REDUCTION STAGE

For a potential acid sulfate soil to develop, sufficient pyrite must accumulate in the sediment such that oxidation of the pyrite will generate acidity in excess of the acid neutralizing capacity of adsorbed bases and easily weatherable minerals, lowering the pH below 4 (Pons et al, 1982).

The requirements for sedimentary pyrite formation are:

1. Anaeroby

   An anaerobic environment is found in flooded sedimentary environments. Limited aeration is supplied by tidal flushing.

2. Sulfate

   The source of sulfate is usually seawater or brackish tidal water, but may also be sulfate rich groundwater. Sulfate is seldom limiting to pyrite formation.

3. Organic Matter

   Some organic matter is codeposited with the sediment, but the most important source is provided by vegetation growing in the sedimentary environment. The vegetative community most commonly associated with acid sulfate soils is mangrove forests of *Rhyzophora* spp. Organic matter is considered to be the most commonly limiting factor in pyrite formation.

4. Bacteria

   Sulfate reducing bacteria of the genera *Desulfotomaculum* and *Desulfovibrio* catalyze the formation of sulfide from sulfate. These bacteria are adapted to wide ranges of pH (5 to 9.5), Eh (-400 to +80 mv), temperature (0 to 70 °C), and NaCl concentration (0 to 12 %) (Rickard, 1973).

5. Iron

   Ferric oxides, hydroxides, and oxyhydroxides are the major sources of iron for pyrite formation. They are commonly transported to the sedimentary environment adsorbed on inorganic and organic particles, and living organisms. Iron is seldom limiting to pyrite formation (Rickard, 1973).

Pyrite is formed when ferrous iron is combined with sulfide produced from dissimilatory bacterial sulfate reduction. The overall process may be described by equation 1:

$$Fe_2O_3 + 4SO_4^{2-} + 8CH_2O + 1/2O_2 \longrightarrow 2FeS_2 + 8HCO_3^- + 4H_2O. \quad (1)$$

The processes involved in sedimentary pyrite formation have been reviewed by Rickard (1973), Bloomfield and Coulter (1973), Pons and van Breemen (1981), Goldhaber and Kaplan (1982), and Pons et al. (1982) and are illustrated in Figure 1.

The reduction of sulfate to sulfide (reaction a, Fig. 1) takes place only under strongly reducing conditions (Dent, 1986). Sulfide production in sediments is almost entirely attributable to dissimilatory sulfate reduction by heterotrophic bacteria. This involves the use of sulfate as terminal electron acceptor, in the absence of oxygen for electrons generated during the oxidation of organic matter. The bacteria involved are obligate anaerobes of the genera *Desulfotomaculum* and *Desulfovibrio*. Rickard (1973) states that sulfate reduction is normally limited by the presence of organic matter. The distribution of organic matter in the sediment appears to influence the distribution of pyrite. Primary organic matter is evenly distributed and has been codeposited with the sediment. This finely divided material is associated with the formation of primary pyrite. Secondary organic matter arises from vegetation growing in the depositional environment and results in the largest accumulations of pyrite, which are closely associated with organic remnants of mangrove root systems. Much of the information relating sulfide production (and thus pyrite formation) to the nature and distribution of organic matter is derived from comparisons of two genera of mangrove. *Rhyzophora* spp. develop stilt root systems covered with root hairs, which are a major source of peaty material building up under these plant communities. *Avicennia* spp. however, produce shallow, widespread roots and soils developing under *Avicennia* spp. are not usually fibrous. Acid sulfate soils are observed much more commonly under *Rhyzophora* spp., emphasizing the importance of organic matter distribution on sulfide production.

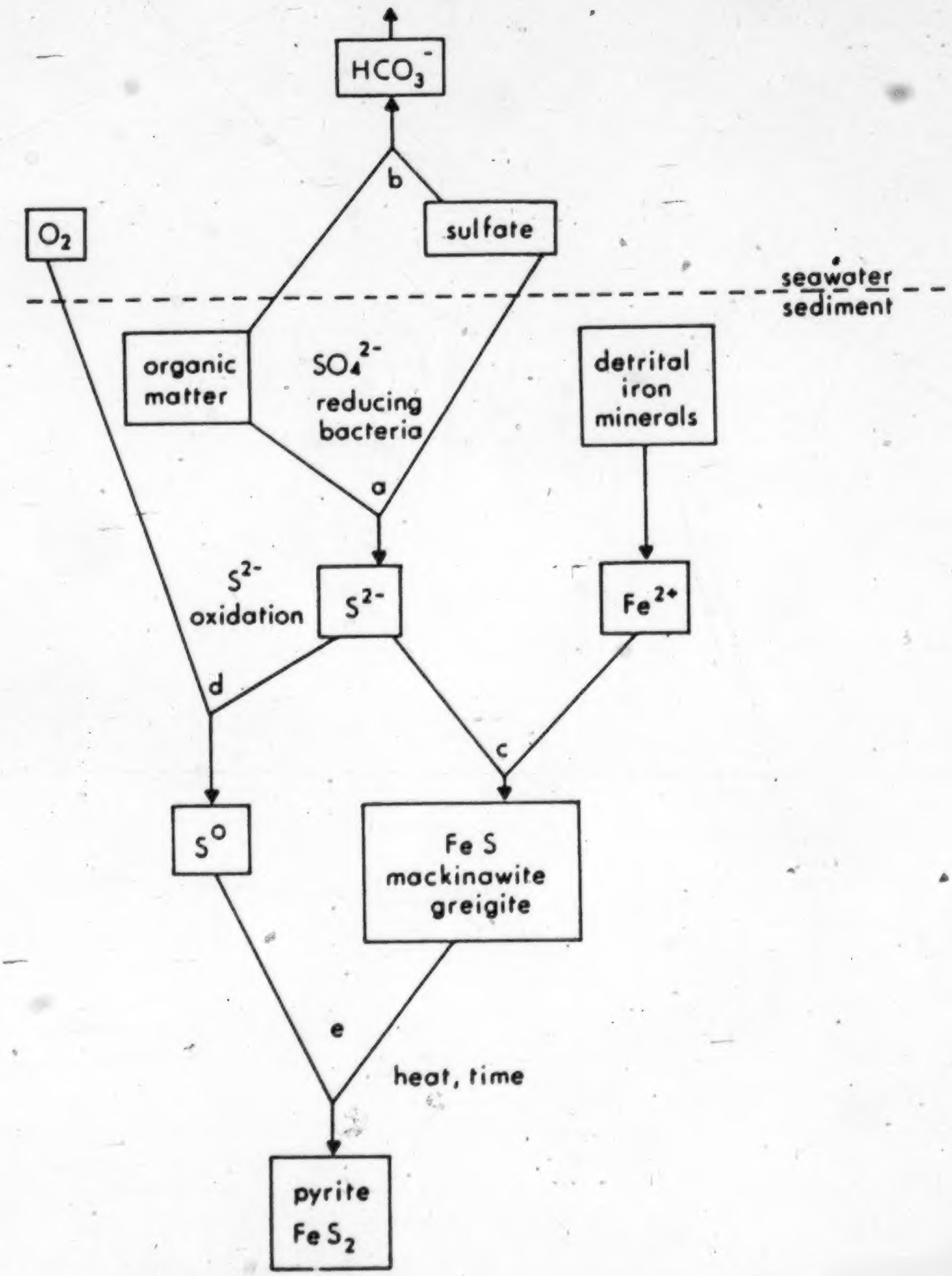
HCO3-
b
O2
sulfate
seawater
sediment
organic matter
SO4 2-
reducing bacteria
detrital iron minerals
a
S2- oxidation
S2-
Fe2+
d
c
S0
Fe S mackinawite greigite
e
heat, time
pyrite Fe S2

FIGURE 1. Sedimentary pyrite formation, illustrating transformations of S and Fe responsible for conversion of sulfate and ferrous iron to pyrite and generation of potential acidity during the reduction stage of acid sulfate soil genesis.

Sulfate reduction rates in sediments may be studied by measuring the changes in sulfate content over time in mud samples brought to the laboratory, or by modelling the pore water composition at various depths. The first method is useful where rates are relatively fast. For slow reaction rates, mathematical modelling is more appealing, provided the nature and depth distribution of competing processes are understood. Factors controlling the rate of bacterial sulfate reduction (Goldhaber and Kaplan, 1982) include the supply of sulfate, the nature and amount of organic substrate, and temperature. In most sediments, sulfate concentrations are above the threshold where rate is not affected by concentration. The type of organic molecules used as electron donors has been shown to affect sulfate reduction rates by a factor of five in laboratory studies (Goldhaber and Kaplan, 1982), but effects of organic matter composition in field situations are obviously much harder to evaluate. Temperature increases the rate of sulfate reduction by a factor of five between 5 and 25 ^{o}C.

Reaction b (Fig. 1) illustrates the removal of alkalinity from the sediment. This removal results from the effects of tidal flushing and is the same mechanism which accounts for the supply of sulfate. It is the removal of alkalinity which creates the imbalance between the potential acid production of pyrite and the acid neutralizing capacity of the soil material. If this alkalinity remains in the sediment it will precipitate as calcium carbonate and will help neutralize acidity during subsequent pyrite oxidation.

In the sediment, ferric ion is reduced to ferrous ion, which combines with sulfide to form ferrous monosulfide, a precurser to pyrite. This is depicted in Figure 1 by reaction c. The formation of ferrous monosulfide occurs rapidly in sediments. The exact nature of the monosulfide formed is still unresolved, but it is unstable with respect to pyrite.

Alternating periods of aeration are required for the oxidation of sulfide to elemental sulfur as illustrated in reaction d, Figure 1. Biological sulfur cycling has been implicated in the formation of elemental sulfur which may be important in pyrite formation during the latter stages of diagenesis, according to the following reaction:

(2) $\langle FeS\rangle + S^{o} \dashrightarrow FeS_2$.

While this reaction occurs slowly (Dent, 1986), it may account for the absence of ferrous monosulfide in older sediments. Van Breeman (1973) states that aqueous polysulfides are probably involved in pyrite formation according to:

(3) $\langle FeS\rangle + S_n^{2-} \dashrightarrow FeS_2 + 2e^-$

where the immediate oxidants are polysulfide anions.

Pyrite accumulations of up to 1% per 100 years are reported by Dent (1986). These rates could result in potential acid sulfate soils forming in 200 to 300 years.

Potential acid sulfate soils are characterized by an excess of pyrite over acid neutralizing capacity of the soil. Pyrite contents are commonly between 1 to 4 % pyrite-S. They are in a reduced state and thus have few pedogenic features. They are usually fine textured, having formed from slow sedimentation, and are unripe, i.e. waterlogged, the material being unconsolidated and of low bearing strength. Potential acid sulfate soils are often high in organic matter, and the pH is near neutral as long as the soil remains saturated (Van ~~Breemen~~, 1982).

2.1.2 OXIDATION STAGE

The transition from a potential to an actual acid sulfate soil occurs when the redox potential of the soil environment increases to the point where pyrite is unstable. This may occur as a result of isostatic rebound of the land mass, lowering of the sea level, drainage for reclamation, or other alteration of the hydrology, either natural or anthropogenic (Van Breemen, 1982).

Pyrite oxidation is a process which involves several types of oxidation-reduction reactions, hydrolysis and complex ion formation, solubility controls and kinetic effects. Reviews of the processes involved have been published by several authors (Bloomfield and Coulter, 1973; van Breeman, 1973; Ivarson et al, 1982; Nordstrum, 1982; Dent, 1986). The oxidation of pyrite occurs spontaneously in aerobic environments. The specific reactions involved are still a matter of study. Nordstrum (1982) describes proposed mechanisms for the various electron transfer reactions associated with pyrite oxidation. The overall process involves several potential rate determining steps, consisting of both inorganic and organic reaction paths.

Figure 2, after van Breemen (1973) illustrates the major pathways of pyrite oxidation. The initial reaction (reaction a, fig. 2) involves the slow release of ferrous ion and the oxidation of pyrite-S to elemental sulfur. The balanced reaction may be summarized as follows:

(4) $FeS_2 + 1/2O_2 + 2H^+ \text{---}> Fe^{2+} + 2S^o + H_2O.$

It can be seen that this process consumes protons, and thus the equilibrium is forced to the right at low pH.

The products of reaction a (Fig. 2) are subject to further oxidation, catalyzed by Thiobacillus bacteria. The chemical oxidation of elemental sulfur to sulfate (reaction b, Fig. 2) is a very slow process, but all species of Thiobacillus are capable of catalyzing the reaction:

(5) $S^o + 3/2O_2 + H_2O \text{---}> SO_4{}^{2-} + 2H^+.$

At near neutral pH, Thiobacillus thiooxidans is the major species involved. Thiobacillus ferrooxidans is more active at pH values below 4. The oxidation of sulfur to sulfate generates protons, leading to a drop in pH.

Ferrous ion released in reaction a (Fig. 2) is slowly oxidized in the presence of oxygen to ferric ion with a half time of reaction of approximately 1000 days (Singer and Stumm, 1970). At pH values above 4.0, ferric ion immediately hydrolyzes to form insoluble ferric hydroxides. This process is depicted by reaction paths (c) and (f) in Figure 2, which may be written as:

(6) $Fe^{2+} + 1/4O_2 + H^+ \text{---}> Fe^{3+} + 1/2H_2O,$

and

(7) $Fe^{3+} + 3H_2O \text{---}> Fe(OH)_3 + 3H^+.$

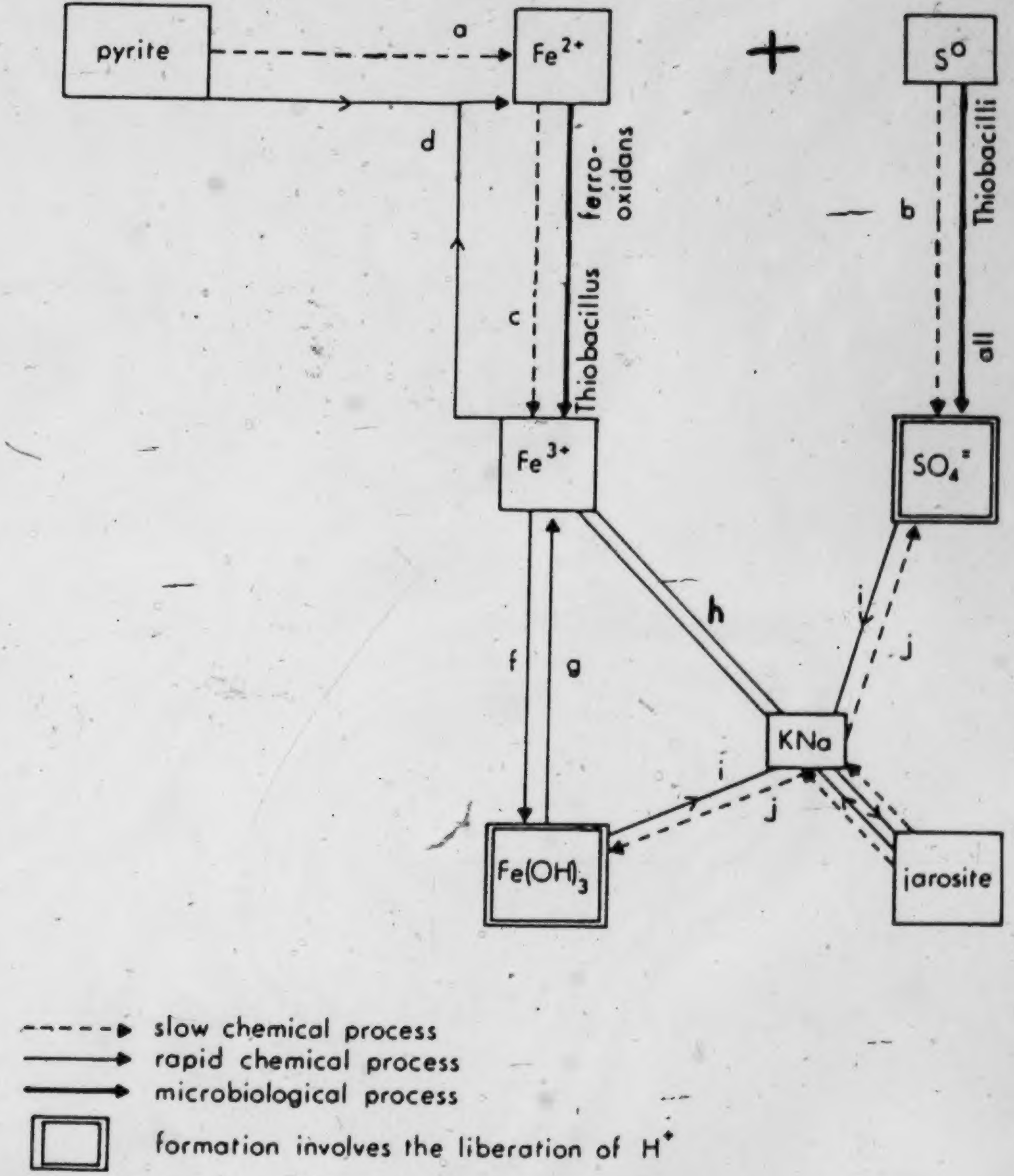
pyrite
a
Fe^{2+}
+
S^o
d
ferro-oxidans
Thiobacillus
b
Thiobacilli
all
c
Fe^{3+}
SO$_4^=$
h
i
j
f
g
KNa
i
j
Fe(OH)$_3$
jarosite
slow chemical process
rapid chemical process
microbiological process
formation involves the liberation of H$^+$

FIGURE 2. Chemical and microbiological processes involved in pyrite oxidation, and subsequent reactions associated with the production of acidity during the oxidation stage of acid sulfate soil genesis.

The oxidation of pyrite by ferric ion (reaction d, Fig.2) occurs much more rapidly than oxidation by dissolved oxygen. As the pH drops below 4, reaction d (Fig. 2) becomes the dominant mechanism. This is a result of increased availability of ferric ion brought about by 1; dissolution of ferric oxides and hydroxides (reaction g, Fig. 2) and 2; bacterial oxidation of ferrous ion to ferric ion by Thiobacillus ferrooxidans (reaction c, Fig. 2). The reaction of ferric ion with pyrite may be expressed by the following equation:

(8) $Fe^{3+} + FeS_2 \text{ ---> } 2Fe^{2+} + 2S^o$.

Microorganisms catalyze pyrite oxidation by lowering the pH and by increasing the supply of ferric ion. Thiobacillus bacteria have been isolated from virtually all acid sulfate soils and their association with pyrite oxidation is well documented (Ivarson et al., 1982). The optimum temperature range for microbial growth is 20 to 40 °C. Below 10 °C, the rate of pyrite oxidation is slowed considerably. These bacteria are also very tolerant to high metal concentrations and are well adapted to survive a wide range of pH.

Numerous iron sulfate minerals may precipitate from acid sulfate soil solutions (Nordstrum, 1982). The most insoluble, and therefore the most persistent of these is jarosite, which also represents a fairly complete oxidation of iron. Under extremely acid (below pH 3.5), oxidizing conditions, the oxidation products of pyrite can be incorporated into jarosite. The production of jarosite is usually associated with soils where the acid neutralizing capacity is minimal. The formation of jarosite is illustrated in Figure 2 by reaction paths i and h. Ivarson (1973) describes the role of Thiobacillus ferrooxidans in jarosite formation. Jarosite occurs as a pale yellow material commonly found along cracks and ped faces in acid sulfate soils. The formation of jarosite, which is a member of the alunite group of minerals, may be expressed by:

(9) $(K,Na)^+ + 3Fe^{3+} + 2SO_4^{2-} + 6H_2O \text{ ---> }$

$(K,Na)Fe_3(SO_4)_2(OH)_6 + 6H^+$.

It can be seen that jarosite formation is a proton generating reaction. It represents, however an incomplete hydrolysis of Fe and SO_4 and the eventual breakdown of jarosite leads to further acidification of the system by the formation of ferrihydrite:

$$(10) \qquad (K,Na)Fe_3(SO_4)_2(OH)_6 + 3H_2O \text{ ---> } (K,Na)^+ + 3Fe(OH)_3 + 2(SO_4)^{2-} + 3H^+.$$

Jarosite is unstable at high pH or under reducing conditions. At high pH it hydrolyzes according to reaction (10), and at low Eh, it undergoes solution-reduction as per the reverse of reaction (9). Jarosite may persist in soils for considerable periods after the major effects of pyrite oxidation have disappeared, and the pH is above 4. Bloomfield and Coulter (1973) describe some "fossil" acid sulfate soils where jarosite is persistent. It is possible that bulk pH data for a soil sample may be misleading in such cases, and the pH in the vicinity of the jarosite may still be very acid. Other explanations could be the presence of an arid environment, insolubility of the jarosite, or sluggish kinetics for the hydrolysis of jarosite to ferrihydrite (reaction j, Fig. 2).

Substitution of Na and H for K in the jarosite structure results in a continuous solid solution series between natrojarosite, hydronium jarosite, and jarosite. There is a strong preference for K in the structure and natrojarosite has been shown to form only after severe depletion of K from the solution (van Breemen, 1973). Substitution of Al for Fe also results in a complete solid solution series between alunite and jarosite. Van Breemen (1973) has reported between 1.4 and 12 % substitution of Al for Fe. There is a strong preference for Fe in soil environments.

The presence of $AlOHSO_4$ has been implied by studies of the aluminum chemistry of acid sulfate soil solutions (van Breemen, 1973). Although no direct evidence for the presence of the material has been obtained, levels of aluminum in solution indicate that this species may control the solubility of aluminum in many acid sulfate soils. It may be that the material is amorphous, and thus not detected by X-ray diffraction.

Acid sulfate soil solutions are frequently supersaturated with respect to $CaSO_4 \cdot 2H_2O$ (gypsum) and this mineral is common, particularly in arid environments. Gypsum occurs over a wide pH range and may be associated with jarosite in low pH, high Ca environments. Gypsum is unstable in the presence of jarosite and should revert to jarosite according to:

$$(11) \quad 4\text{gypsum} + 3Fe_2O_3 + 2K^+ + 6H^+ \text{--->} 2\text{jarosite} + 4Ca^{2+} + 5H_2O.$$

Gypsum has been reported to occur at pH values as low as 2 in an environment depleted in K (van Breemen, 1973). $CaCO_3$, other Ca minerals, or adsorbed Ca^{2+} have been considered as the sources of Ca for gypsum formation. Dutch soils with gypsum have $CaCO_3$. Acid sulfate soils in Thailand soils are flushed with Ca rich floodwaters.

The effects of pyrite oxidation on soil materials are related to the tremendous quantities of sulfuric acid generated. The fate of the iron released determines the amount of acidity generated. Maximum acid production results when all released iron is hydrolyzed to solid ferric hydroxide. This situation results in the release of 4 moles of H^+ for each mole of pyrite oxidized. If jarosite is the end product, 3 moles of H^+ are produced for each mole of pyrite oxidized. These two reactions are favored because of the strong tendency for ferric ion to hydrolyze. Usually a large portion of pyrite-Fe is incorporated into jarosite, which, over time, hydrolyzes to ferric oxide. Very little Fe^{3+} leaves the system in solution because Fe^{3+} is insoluble at high pH and is incorporated into jarosite at low pH.

The pH of an acid sulfate soil is determined by the amount of sulfuric acid produced and the acid neutralizing capacity of the soil material. Upon oxidation, pH values as low as 2.0 have been reported in the field, and as low as 1.3 in the laboratory. If excess calcium carbonate is present, the pH upon oxidation may remain in the 7.2 to 7.8 range. Typical values for soil horizons measured in the field are between pH 3.0 and 4.0. The pH is strongly buffered in certain ranges depending on the source of the acid neutralizing species.

2.2 ACID SULFATE SOILS IN WESTERN CANADA

Acid sulfate soils have been described in Manitoba (Ehrlich et al, 1958), Saskatchewan (Mermut et al, 1985), Alberta (Reeder and Odynsky, 1965; Pawluk, 1971; Pawluk and Dudas, 1978), and British Columbia (Clark et al, 1961; Clark and Green, 1964) in Western Canada. The actual extent of acid sulfate soil conditions in this region is not known, owing to incomplete soil survey information in areas where the soils are found.

The occurrence of acid sulfate soils in Western Canada is associated with portions of the landscape where soft gray shales of Cretaceous age outcrop through Quaternary glacial deposits. The oxidation of pyrite in the shale results in the highly acidic parent materials in which these soils develop. Problems associated with soil acidity may occur in areas where the shale outcrops, where the tills are composed largely of the shale material, or in acidic groundwater discharge areas.

In northwestern Alberta, Cretaceous age shales of the Kaskapau formation constitute a major component of the bedrock. Great thicknesses of these materials were removed prior to glaciation (Bayrock, 1959). These materials are overlain by surficial till, fluvial, and eolian deposits. The land surface in general consists of high plain remnants, gently sloping areas, flatlands, and incised valleys of the major streams (Reeder and Odynsky, 1965). The high plain remnants, described as the Clear Hills, Naylor Hills, Hawk Hills, and Buffalo Head Hills are outcrops of the shale bedrock, and are the locations where acid sulfate soil conditions are likely to be expressed. If these locations have thin glacial deposits the acid nature of the shale will strongly influence soil properties. Much of the area, however has significant cappings of till, and the acidic shale material does not control soil properties. The lower lying areas and gently sloping areas consist largely of lacustrine deposits and tills of varying composition, some of which are acidic.

Soils mapped as Boundary Complex (after Boundary Lake in northern British Columbia) in northwestern Alberta (Reeder and Odynsky, 1965) have formed in upland positions from acid shale parent material. These well drained soils are characterized by very low pH and base saturation values, and deep reddish colored Bt horizons. The soils lack evidence of strong geochemical or physical modification (Pawluk and Dudas, 1978). Morphological characteristics such as degree of development, eluviation and thickness of the A horizon, and amount of illuviated iron, aluminum and clay in the B horizon are highly variable. Scheeler and Odynsky (1968) described these soils as a podzolic complex, while further examination has provided justification for placing the soils in the Luvisolic order as Dark Gray Luvisols (Pawluk and Dudas, 1978). The Canadian System of Soil Classification, however, excludes them from the Luvisolic order because of the low base saturation and high extractable iron content resulting from natrojarosite dissolution.

Soil properties within the Boundary complex are extremely variable over short distances, due to the steep terrain and the effects of local hydrology on soil properties. Thus the extent of plant growth problems associated with these soils may not directly relate to the areal extent of the Boundary soil map units. In any case, approximately 58750 ha of Boundary soil have been mapped in northwestern Alberta. Considering that soil surveys in this area of the province are incomplete, this must be regarded as a conservative estimate of the actual extent of these soils. It appears that severe forest growth restrictions within the map units may be confined to small ridge tops and represents a minor proportion of the areas mapped as Boundary complex.

Early literature relating to Boundary soil has focused on the unique chemical, mineralogical, and morphological features of this soil, and of the problems associated with classification. Clark and Green (1964) compared Boundary soil profiles from northeastern British Columbia with two Solods from the same area. They concluded that Boundary soil should be classified as an Orthic Gray Wooded soil because Bt horizons had higher clay content than A horizons and C horizons, and also had clay skins on ped faces. They found no accumulation of iron oxides and organic matter in the B horizon to place the soil in the Podzolic order, and no prismatic structure necessary for a Solod, although chemical characteristics could describe a Podzol (low pH, base saturation) or a Solod (exchangeable Mg + Na > Ca).

Pawluk and Dudas (1978) investigated soil processes in a Boundary soil profile near Peace River, Alberta from the perspectives of soil genesis and classification. They describe the two dominant processes of soil formation as (1) mineral weathering resulting in the release of iron and smaller quantities of aluminum, and (2) the reorganization of soil materials by biological, physical, and to a lesser extent, physical chemical processes. The dominant weathering reaction is the decomposition of pyrite and natrojarosite, and the deep reddish color of the Bt horizon may be attributed to the formation of goethite during iron hydrolysis. The reorganization of shaly material by biological and freeze-thaw processes is indicated. Despite the acidic nature of the material, micromorphological features indicate that biological factors dominate in the genesis of this soil. The extent to which this was true in earlier stages of soil development is uncertain. Pawluk and Dudas (1978) state that the soil may best be classified as a Dark Gray Luvisol. They also discuss mineralogical transformations in the profile, specifically the depotassification of mica and its reversion to vermiculite in the surface horizons.

Recent investigations of acid sulfate soils in upland positions in Texas (Carson and Dixon, 1983) and in Saskatchewan (Mermut et al, 1985) have sought to determine what mineralogical features are associated with acid sulfate weathering, and what effects are preserved during subsequent soil development. The presence of jarosite is a useful indicator of pyrite decomposition, but its persistence after soil pH has risen above 4 is somewhat puzzling. Carson and Dixon (1983) describe jarosite as pseudomorphic after pyrite (cubic crystal system), indicating recrystallization as a mode of formation, rather than solution precipitation.

Mermut et al (1985) investigated submicroscopical features of an acid sulfate soil in Saskatchewan by excavating to a depth of 5 m. They found natrojarosite in the 2.5 to 4.0 m zone, and intact pyrite crystals below 4.0 m. They state that pyrite and natrojarosite coexist in this region. Crystals of gypsum were also found in this zone. They postulate that natrojarosite is formed by solution precipitation, and not by recrystallization as proposed by Carson and Dixon (1983). This conclusion was based on the fact that the material was crystalized in the rhombohedral form (hexagonal crystal system) and not the cubic system as stated by Carson and Dixon (1983), although the two forms resemble each other. They believe that the natrojarosite forms in the cavities created by H_2SO_4 dissolution of clay minerals and that jarosite persists because of its low solubility. Solution precipitation as a mechanism of formation is consistent with the distribution of jarosite on ped faces and cracks.

Curtin and Mermut (1986) discuss the behaviour of montmorillonite in the same profile described above. Their calculations, based on thermodynamic considerations, show that montmorillonite is stable under the extremely acid conditions present in the lower solum, and they attribute this, in part, to a lack of leaching which prevents the removal of weathering products. A soil solution of high Na and Fe concentration allows the montmorillonite to persist.

Dudas (1984) reported enriched levels of arsenic in Boundary soil samples. This was attributed to the scavenging by ferric oxyhydroxides of arsenic released during pyrite decomposition. Levels of arsenic in iron oxide veinlets occurring in the profile were found to be as high as 10 to 50 times normal background levels.

Current research on acid sulfate soils in upland positions is not directly related to improving these soils for production. The areal extent of these soils in North America does not justify large outlays on management - related research. The major value of research on these soils lies in improving the understanding of the latter stages of acid sulfate soil genesis, in providing useful case studies for solution chemistry/mineral weathering model development, in providing a source of information regarding geochemical behaviour of trace elements, in furnishing a possible explanation for the origin of soil acidity and soil salinity of associated soils, and in serving as natural analogs for areas affected by anthropogenic acid deposition or exposure during mineral extraction.

3. PLANT-SOIL INTERACTIONS AT LOW PH

The effects of soil acidity on plant growth have been reviewed by Jackson (1967), Rorison (1973), Foy et al. (1978), Foy (1984), and others. Production problems on acid soils usually arise from a complex of factors that affect the growth of different plants through different physiological and biochemical pathways (Foy et al., 1978). According to Liebig (in Gauch, 1972) plant growth is directly proportional to the supply of the nutrient present in the minimum. The Law of the Minimum can be expanded to include other plant growth factors such as water, toxic effects, or freedom from disease. For this reason, a holistic approach is required when investigating plant-soil interactions. Such an approach should consider the effects of chemical, physical, and biological processes occurring at the root-soil interface. Soil properties such as nutrient and toxin levels, moisture status, and organic matter transformations must be considered in view of plant characteristics such as tolerance to phytotoxins, rooting habit, and symbiotic and pathogenic relationships in order to correctly diagnose the causes of growth deficiencies.

3.1 CHEMICAL INTERACTIONS

3.1.1 SOIL FACTORS

The pH of a soil is stabilized within certain ranges by the reaction of inorganic soil components with the soil solution. The characteristic reactions occurring comprise the proton buffer systems (Khana and Ulrich, 1984). At pH values between 5.0 and 4.2, solution pH is buffered primarily by the exchange of protons in the solution for cations held on the cation exchange sites of the clay minerals. The buffering capacity of this system is equal to the cation exchange capacity. These exchange reactions result in (1) the release of nutrient cations into the soil solution which are subject to leaching, and (2) replacement of hydrogen ions for aluminum in the clay mineral lattice, leaving an aluminum saturated exchange complex.

Below pH 4.2, the aluminum buffer system stabilizes solution pH through hydrolysis reactions such as:

(12) $Al(OH)_3 \text{ ---> } Al^{3+} + 3(OH)^-$.

The dissolution of hydroxy aluminum compounds consumes protons. A major feature of soil solutions in this pH range is the presence of high concentrations of monomeric aluminum ions, which are toxic to plant roots. The buffer capacity of this system of reactions is much greater than that of the C.E.C. system, due to the high aluminum content of most soils, and the triple valency of aluminum ions.

The iron buffer system is effective in controlling soil pH below pH values of 3.2. One of the reactions responsible for this effect can be shown by:

(13) $Fe(OH)_3 + H^+ \text{---> } Fe(OH)_2^+ + H_2O$.

In acid sulfate soils Fe hydrolysis reactions have important effects on the solution pH. One consequence of these reactions is the release of ferric ion in solution, which is susceptible to eluviation, leading to the drab gray color present in acid sulfate soils. Due to the large amounts of iron in soils, this system can buffer large inputs of acidity.

The concentration of a particular ion in the soil solution is controlled by pH, redox potential, and the nature of solid phases. Since the equilibrium concentration of an ion is a function of the concentration of the ions it reacts with, through the Ksp and free energy change for the reaction, and since the hydrogen ion is involved in all aqueous reactions, the influence of pH on the solubility of the elements is established. Different reaction rates, which can be affected by the activities of microorganisms, result in a solution that is never at equilibrium, but the tendency of the system is to approach the equilibrium solution concentration for a particular solid phase.

Plant roots are sensitive to the ionic composition of the soil solution. The absorptive powers of root membranes determine the required solution concentration of nutrient ions for sufficient plant uptake. Similarly, the exclusion of toxic ions requires either selection of nutrient ions only for uptake, or active removal of toxic ions against the concentration gradient. The level at which a particular element becomes toxic depends on the ability of the plant to exclude it from sensitive metabolic locations. Acid soils impinge on plant growth by being deficient in nutrient ions and by having toxic quantities of other ions in solution.

Bohn et al. (1979) describe the geochemical behaviour of nutrient elements on the basis of their ionic potential. Ionic potential is defined as the ratio of crystallographic radius to ionic charge, and describes the relative attraction of an ion for protons. Elements of high ionic potential, including Ca, Mg, K, and Na, are highly soluble and occur in soils as hydrated cations. The major reserve of these elements for plant uptake is the cation exchange complex. Elements with intermediate ionic potentials, such as the transition metals and aluminum, are characterized by a tendency to form insoluble hydroxides. The nonmetals B, P, and S, and Mo are small, highly charged ions which repel protons and exist as relatively mobile oxyanions. Each of these broad groupings of elements is affected differently by soil pH.

In acid soils, deficiencies of Ca and Mg occur because these ions are released from the ion exchange complex and leach from the root zone. Since a major source of Ca in soils is $CaCO_3$, which is absent at low pH, there may be no replenishment of leaching losses. Sources of Ca in acid soils include Ca feldspars, which, if present release Ca by hydrolysis, and gypsum ($CaSO_4 \cdot 2H_2O$) which precipitates in the presence of sulfate and is an important Ca source in acid sulfate soils. Plants require large quantities of Ca, however, and these sources may not supply sufficient amounts in all situations. This example illustrates an important concept of soil nutrient availability in acid soils, that is soluble cations will be depleted by leaching or plant uptake unless there is continuing release of the cation from the solid phase, or it is supplied in the percolating waters. The primary sources of K in soils of temperate regions are micaceous and feldspar minerals, and as long as these minerals are present some K will be supplied. Hydrolysis of silicate minerals is enhanced at low pH.

Deficiencies of the micronutrient transition metals are not common in acid soils. This is due to the dissolution of the oxyhydroxides of these elements, which releases sufficient quantities to meet the relatively small requirements of plants. Reported deficiencies of Zn and Cu in acid soils are related to extensive leaching.

The elements P and Mo are present in the soil as oxyanions and are immobilized at low pH by adsorption. Fixation results from the amphoteric nature of Al and Fe oxyhydroxides, and amorphous soil materials such as allophane. Protonation of exposed OH^- groups on these materials, and at the edges of clay minerals, particularly kaolinite, results in positively charged surfaces at low pH. Retention and fixation of P are discussed by Tan (1982). P retention is a reversible coadsorption of P with exchangeable Al, Fe and Mn acting as bridges. Solution concentration of P held by retention is governed by the Gapon equation. Fixation occurs when P reacts with Al and Fe hydrous oxides according to the following equation:

(13) $Al(OH)_3 + H_2PO_4^- \dashrightarrow Al(OH)_2(H_2PO_4) + OH^-$.

This reaction occurs with Al, Fe, and Si minerals, or between these elements in solution. The resultant P compounds are insoluble, and ultimately revert to minerals such as variscite ($AlPO_4 \cdot 2H_2O$) and strengite ($FePO_4 \cdot H_2O$). Reaction with kaolinite clays results in the replacement of octahedral Al with P. A similar effect restricts the availability of Mo at low pH. B is less affected by fixation reactions and is more mobile at low pH, existing as undissociated HBO_3.

The concentration of toxic elements is controlled by the same factors that affect nutrient ions. All the micronutrients, and many trace elements, have a phytotoxic nature at excess solution concentrations. As discussed previously the solubility of Al hydroxides at low pH, and the presence of large quantities of exchangeable Al^{3+}, accounts for the presence of high levels of Al^{3+} in acid soils. Al toxicity is the most commonly diagnosed growth limiting factor in strongly acid soils. Toxicity of Fe and Mn has been documented as well, although these elements are usually only toxic under reducing conditions. The consideration of oxidation state of the metal is important for Cr as well. The toxicity of the other transition metals such as Cu, Ni, and Zn is determined by the solubility of the hydroxide forms at the pH level of the soil. Since these elements occur primarily as minor contaminants in silicate minerals the nature of the solid phase controlling solubility may be difficult to determine. Situations where these elements have been shown to be toxic are usually related to anthropogenic deposition from industrial sources. Elements with low ionic potentials such as As are not expected to be a problem in acid soils due to fixation. Liming an acid soil that contained high background levels of As could result in mobilization of large quantities of this element.

3.1.2 PLANT FACTORS

Imbalances of nutrient and toxic ions in acidic soil solutions cause restricted plant growth. The effects of elemental imbalances on individual plant species are highly variable. The deficiency symptoms for a particular element depend on (1) the function of the element in the plant and (2) whether or not the element is readily translocated from old leaves to younger leaves (Salisbury and Ross, 1985). Likewise, elemental toxicities induce symptoms based on the metabolic system affected and the mechanism of toxin transport within the plant. Plants have evolved various response mechanisms which enable them to exploit harsh chemical environments. This section will describe the effects of common acid soil nutrient deficiencies and elemental toxicities on the basis of ion uptake and role in plant metabolism.

Hydrogen

The toxicity of H ions has been discussed by Foy (1984). Excess H ions affect membrane permeability by competing for absorption sites, interfering with ion transport, and causing leakage of absorbed nutrients. The demand of a plant for other nutrients, particularly Ca may be increased by excess H. In the absence of other toxins most plants can tolerate pH values of 4.0 or lower.

Aluminum

Aluminum is not a required plant nutrient. The toxic effects of Al on plant roots are well documented (Bloomfield and Coulter, 1973; Russell, 1973; Foy, 1984; Shkolnik, 1984; and others). The following harmful effects of aluminum have been described:

1. interferes with cell division.
2. increases cell wall rigidity.
3. reduces DNA replication.
4. decreases root respiration.
5. interferes with sugar phosphorylation.
6. interferes with uptake, transport, and use of Ca, Mg, K, P, and Fe.

Many of these effects result from the strong affinity of Al for PO_4^{3-} ligands. Al binds to esteric P in DNA, inhibiting mitosis. Al binds to ATP, restricting oxidative glucose phosphorylation by the enzyme hexokinase. The stiffening of cell walls restricts root elongation when Al combines with pectins of the cell wall. In most plants, Al is not translocated from root to shoot, therefore symptoms of Al toxicity are expressed primarily in roots. Since Al inhibits cell division and elongation, roots suffering from Al toxicity are short with club shaped tips, and lack lateral branches.

Calcium

Clarkson and Hanson (1981) review the role of Ca in plants. The ability of Ca to coordinate with a variety of ligands, producing complex cross linking, and showing weak geometrical demands explains the role of Ca in forming gels in the middle lamella. This is why plants require such large quantities of Ca, and why it is essentially nonmobile in plants. Ca bridging of phosphate and carboxylate groups of membrane phospholipids may account for the role of Ca in increasing stability and reducing the leakiness of membranes. Small amounts of Ca are required as a cofactor for enzyme activation. Deficiencies of Ca are manifest in young tissues and meristematic regions because Ca in older tissues cannot be translocated to meet the requirements of new tissues. Meristematic zones are susceptible because active cell division requires the formation of middle lamella (Salisbury and Ross, 1985). Root and shoot dieback are symptomatic of Ca deficiency resulting in twisted and deformed tissues. The stabilizing effect of Ca on plasma membranes helps explain the ability of Ca to reduce the effects of various metal toxicities.

Magnesium

There are many enzymatic reactions involved in respiration, ATP conversions, CO_2 fixation, and protein synthesis that require or are promoted by Mg (Clarkson and Hanson, 1981). Mg is a small, strongly electropositve cation which is readily mobile and coordinates with limited geometric distortion. These properties are applicable to the role of Mg in group transfer processes. The presence of Mg in chlorophyll is related to it's octahedral coordination. Deficiency of Mg causes interveinal chlorosis of older leaves.

Potassium

The role of K in plant metabolism involves enzyme activation, stomatal movement, and charge balance during anion transport. Plants require large amounts of K. Deficiency of this highly mobile element is expressed as localized chlorosis and mottling of older leaves.

Phosphorous

P is found in nucleic acids, ATP, membrane phospholipids, and certain proteins. The stability of PO_4^{3-} accounts for it's role in capture, transfer, and recovery of energy. The effects of P deficiency are generalized over the entire plant (Salisbury and Ross, 1985), with a dark green color being most commonly observed.

Iron

Fe is an important component of enzymes responsible for electron transfer reactions. Fe provides the loci for variable redox potentials and produces transferable electrons. Catalytic and structural roles of Fe are suspected, but not well understood (Clarkson and Hanson, 1981). Fe is absorbed by plants as Fe^{2+}, Fe^{3+}, or chelated Fe. Fe deficiency is identified by interveinal chlorosis of younger leaves, since Fe is not translocated in the phloem (Wallihan, 1966). While Fe is readily available in acid soils, excess Cu, Zn, and Ni can displace Fe from chelate complexes, preventing translocation of Fe from root to shoot, and inducing Fe deficiency (Mengel and Kirkby, 1978).

Both Fe^{2+} and Fe^{3+} can be toxic to plants. Fe^{2+} is likely to be toxic in flooded soils while Fe^{3+} may be toxic under aerated conditions below pH 3.5. Symptoms of Fe toxicity vary among different plant species (Foy et al., 1978). Roots appear thickened and accumulate inorganically bound P. Fe toxicity is also expressed in shoots as dark green foliage (possibly related to P deficiency) on lower leaves. Excesses of Fe may induce or aggravate deficiencies of other transition metals, especially Zn and Mn, possibly by competing for uptake or chelation.

Boron

Although no specific enzymatic requirement for B is known, Kabata-Pendias and Pendias (1984) relate the physiological functioning of B to four main processes:

1. carbohydrate metabolism and transport.
2. nucleic acid and phytohormone synthesis.
3. formation of cell walls.
4. tissue development.

The uptake of B is considered to be primarily passive as undissociated HBO_3 (Clarkson and Hanson, 1981). B deficiency results in degeneration of meristematic tissues, breakdown of parenchymal cell walls, and abnormal development of vascular tissues.

These factors lead to morphological irregularities such as terminal growth dieback, rosetting, stimulation of lateral buds, leaf curling, wilting, chlorosis, and cracked or dead stems. B deficiency may occur after liming of acid soils.

Tissue B levels only slightly higher than normal may be associated with toxicity. Symptoms of B toxicity include leaf tip yellowing followed by progressive necrosis. Leaves take on a scorched appearance and may drop prematurely (Bradford, 1966).

Manganese

In laboratory studies, Mn can substitute for Mg in many enzymatic reactions, but the much higher levels of Mg in plants suggests that this does not occur to any great extent in nature. Specific requirements for Mn relate to a redox role during photosynthetic oxygen evolution in the chloroplasts (Clarkson and Hanson, 1981). Mn is absorbed primarily as the divalent cation, it can be partially mobilized from the leaves, and is partially phloem mobile. Mn is not likely to be deficient in acid soils.

Toxicity of Mn is commonly reported for acid sulfate soils, particularly under reducing conditions. Foy et al. (1984) describe the physiological effects of Mn toxicity as related to the destruction of auxin, possibly through the activation of IAA oxidase. Mn also appears to influence DNA replication, increasing mutations and stimulating viral DNA production, thus predisposing plants to viral diseases. Symptoms of Mn toxicity are often observed in plant tops before growth is severely restricted, and include marginal chlorosis of new leaves and necrotic spots on leaves. Excess Mn may induce Fe deficiency.

Zinc

Zn is incorporated into a multitude of metalloenzymes (Shkolnik, 1984) and may substitute for Mn and Mg. Zn is also an activator of metalloenzyme complexes. Functions of Zn in plants relate to metabolism of carbohydrates, proteins, and phosphate, and also to auxin, RNA, and ribosome formation (Kabata-Pendias and Pendias, 1984). Zn may also influence the stability of membranes. Zn^{2+} is absorbed metabolically and translocation within the plant depends on the availability of Zn to the roots. Zn accumulates in roots and mature leaves and may be concentrated in the vacuole, cell membranes or chloroplasts. Zn is unlikely to be deficient in acid soils and toxicity is usually associated with polluted soils. Mengel and Kirkby (1978) describe the ability of plants to tolerate very high levels of Zn near ore deposits and spoil heaps. Zn toxicity results in a reduction in root growth and leaf expansion, followed by chlorosis. High levels of Zn have been have been shown to depress the uptake of Fe and P.

Copper

Cu participates in redox enzymes and is essential to photosynthesis as an electron carrier in the light reactions. Cu is a strong competitor for ligands and thus is potentially toxic to many metabolic processes (Clarkson and Hanson, 1981). Both passive and active uptake of Cu occur, with passive uptake being especially important in toxic situations. Most Cu absorbed by plants remains in the roots immobilized within the cell walls. Deficiency symptoms tend to appear first in young tissues, while toxicity of Cu leads to tissue damage, elongation of root cells and altered membrane permeability.

Molybdenum

Mo is a required component of nitrate reductase and of the nitrogenase enzyme in symbiotic N-fixing bacteria. Of the required plant nutrients, Mo is present in plants in the smallest quantities. Deficiency symptoms may resemble N deficiency, with restricted growth and pale leaves. Plants grown in NH_4^+ without Mo do not exhibit deficiency symptoms. Deficiency is observed in older and middle leaves, which turn yellow with rolled leaf margins.

Cobalt

Co has not been shown to be essential for higher plants, although it is essential for certain algae and for symbiotic N - fixation. The role of Co in N - fixation relates to the cobamide coenzyme (Mengel and Kirkby, 1978). The requirement for Co in this system is extremely low. Co toxicity in natural systems is extremely rare.

3.2 PHYSICAL INTERACTIONS

Soil physical properties affect plant growth through the effects of temperature, aeration, and bulk density on root growth, and through the status of soil water and its availability to plants. Russell (1973) describes the effects of pore size and soil strength on root growth. Roots are dependent on the anchoring effects of root hairs to allow the root tip to force its way through the soil. Roots have difficulty penetrating heavy soils with a bulk density greater than 1.5 to 1.6 Mg m^{-3}.

The soil moisture potential is a measure of the energy required to remove water held by soil particles. Rooting density, plant water potential, soil water potential and hydraulic conductivity will determine if there is sufficient water in the soil to meet the needs of the plant (Hillel, 1982). In acidic soils the presence of toxic factors which limit root growth may predispose plants to moisture stress by restricting water uptake from lower soil horizons. This type of relationship between a toxic factor and a physical factor such as moisture status is common in the study of plant - soil systems.

3.3 BIOLOGICAL INTERACTIONS

The nitrogen cycle is affected by pH. In soils below pH 4.5, the action of nitrifying bacteria is severely restricted, probably by toxic levels of aluminum. For this reason, plants adapted to very acid soils must be able to exploit ammonium as their principal source of N (Mengel and Kirkby, 1978). Nodule forming bacteria are inactive below pH 4.5, affecting the ability of leguminous species to exploit acidic environments. The effects of soil acidity on plants may be mediated through effects on mycorrhizal associations, which are pH dependant. Acidity can affect the viability of the association even when the fungus and the plant are both present.

Nutrient cycling is achieved through the actions of bacteria which mineralize nutrients from dead plant materials. In acidic environments, decomposers encounter problems similar to those described for plants, especially elemental toxicities. Nyborg and

Hoyt (1978) discuss the effects of soil acidity and liming on the mineralization of soil N. They conclude that increases in mineralization following liming may be short lived, indicating that low pH values may not restrict mineralization in all soils. The effects of soil acidity on nutrient cycling organisms may affect nutrient supply to plants if mineralization is inhibited.

Another consideration is the impact of pathogens on plant growth. The susceptibility of a plant to devastating attack by pathogens or insects is inversely related to plant vigour. Thus plants which are growing poorly, are deprived of nutrients, and are suffering toxic reactions are predisposed to disease or insect attack.

3.4 PLANT RESPONSE TO LOW pH ENVIRONMENTS

Plants capable of exploiting acidic environments have evolved mechanisms enabling them to extract sufficient nutrients from depleted soil solutions while excluding toxic ions from sensitive metabolic sites. Clarkson and Hanson (1981) describe some characteristics which facilitate colonization of nutrient poor sites:

1. adjustment of growth rate to nutrient supply
2. efficient acquisition of nutrients
3. efficient internal economy involving redistribution within the plant and/or lower requirements at functional sites.

The adjustment of growth to nutrient supply depends on the sensitivity of growing tissues to reduced concentrations of a particular element. Growth rate drops quickly in response to N deficiency while for K, P, and S growth rate responds more slowly to depletion (Clarkson and Hanson, 1981). For elements which are not phloem mobile, such as B and Ca, growth of meristems is halted abruptly by nutrient deficiency.

There are several mechanisms by which plants can increase nutrient acquisition. By allocating more energy to root growth, the exploitation of soil reserves is improved. Soil availability of Fe may be improved through the exudation of chelates or by lowering the pH of the rhizosphere. The transport activities of membranes may be altered during periods of nutrient stress.

In addition to factors which increase the uptake of nutrients, the redistribution of nutrients within the plant may improve the supply of a nutrient at critical locations within the plant. The utilization of the most efficient metabolic pathways associated with a particular nutrient lowers the absolute requirement for the nutrient.

Many of the factors described above are genetically controlled. The genetic basis of tree nutrition was reviewed by Goddard and Hollis (1984). The development of morphological and physiological characteristics relating to root growth, mycorrhizal associations and nutrient redistribution have been compared with productivity and yield for different genotypes of several forest tree species.

Saric (1983) states that the requirements of individual plants are very specific, while higher botanical categories have much broader requirements. For the study of requirements of a plant species, the variation in nutrient requirements across the same higher botanical category (i.e. same genus) must be considered. Varietal differences in plant morphology, anatomical features of cells, ion uptake and translocation, nutrient content, physiological and biochemical processes, and yield are the criteria which may be useful in determining the specificity of mineral nutrition.

The physiology of metal tolerance in plants was reviewed by Woolhouse (1983). Different plants have evolved different mechanisms to tolerate the same metal (e.g. Cu) thus the study of metal tolerance can be complex. In addition, some mechanisms are highly metal specific while others provide protection from a variety of metals. There are two basic strategies of metal tolerance. In general, plants may employ external mechanisms where the metal is excluded from the symplast, or internal mechanisms of metal tolerance, where the metal is detoxified in the cytoplasm. Several exclusion mechanisms have been described (Taylor, 1985):

1. immobilization of metals in the cell wall
2. exudation of chelate ligands
3. redox barrier at the plasma membrane
4. pH barrier at the plasma membrane.

It is known that root cell walls bind metals and the extent of binding may be related to tolerance for a particular metal. Cell wall binding alone cannot explain tolerance for metals, although it may contribute to tolerance. The major argument against cell wall binding is the limited capacity of the cell wall to absorb metals when compared to the amounts of metal present in the soil (Woolhouse, 1983).

Chelation of metal ions is known to reduce uptake, accumulation and phytotoxicity of metals such as Al, Cd, Co, Cr, Cu, Mn, Ni, and Zn in nutrient solutions (Taylor and Foy, 1985). The effect appears to be related to competition between root uptake sites and chelates for metal ions. In addition, metals absorbed as chelated complexes may be less toxic once inside the cytoplasm. This observation raises the question of whether or not chelated complexes must be split before root uptake. There is little direct evidence that plants exude chelators as a response to metal toxicity (Taylor, 1985).

The best known example of a redox barrier at the plasma membrane occurs in rice plants, which are capable of oxidizing Fe^{2+} to Fe^{3+} by the transport of oxygen to the roots. A positive correlation has been observed between the weight of ferric coatings on the roots and root weight of rice. The pH barrier hypothesis was studied recently by Taylor and Foy (1985) to explain differential tolerance of wheat (Triticum aestivum) cultivars to aluminum. Tolerant cultivars tend to maintain a higher pH when grown in nutrient solutions. The authors relate a higher pH in the nutrient solution to preference for NO_3^- over NH_4^+ when both forms of N are present. This hypothesis still could not explain all aspects of tolerance in these plants, however.

Internal metal tolerance may be provided by several mechanisms:

1. compartmentalization of metal in the vacuole
2. evolution of metal tolerant enzymes
3. detoxification through formation of stable metal chelates
4. detoxification through binding to metallothionines.

Woolhouse (1983) discusses internal tolerance to Zn and Cu. Zn may accumulate in the vacuole as Zn oxalate. The presence of specific metal binding proteins in animals and plants may be related to metal tolerance. The ability of some plants to accumulate large quantities of potentially toxic metals suggests the presence of internal tolerance mechanisms.

4. MATERIALS AND METHODS

4.1 APPROACH TO PLANT - SOIL ANALYSIS

This study was conceived as an exploratory study into plant growth conditions along a soil catena. Vegetation analysis was conducted using several techniques and the results were interpreted with respect to soil chemical and physical characteristics. Total elemental analysis for plants and soils was carried out with instrumental neutron activation analysis (I.N.A.A.). Standard soil tests were used to determine the nutrient status of the soil. Elemental composition of vegetative materials was determined using standard plant tissue techniques. Clay mineralogy and soil physical properties such as bulk density, moisture retention characteristics, and microstructure were determined. In an attempt to separate the effects of soil chemical factors from physical and biological effects, a greenhouse study was conducted using bulk soil samples collected from the catena. Growth differences observed in the greenhouse experiment are related to soil chemistry, rather than physical or biological factors.

4.2 STUDY SITE

The study area is located 20 km south of the Peace River, near the hamlet of Blueberry Mountain, in N.W. Alberta. The legal location is NE7 - Twp. 82 - Rge. 8 W6. The site is situated on a bedrock high, which is one of several low hills separated by interconnected flatlands. The hill on which the study site is located occupies approximately 5000 ha and is drained by a series of intermittent creeks which generally flow in a N.W. to S.E. direction. Steep sided ridges separate the small drainages, with a frequency of approximately 100 m. A representative soil catena was selected for study on a south facing slope 50 m long, with an average slope of 16 %. The elevation change over the catena is 7 m. The following criteria were used for site selection:

1. Severely inhibited growth of aspen in upper slope position.
2. Soil properties characteristic of the Boundary complex.
3. Average slope conditions for the area.

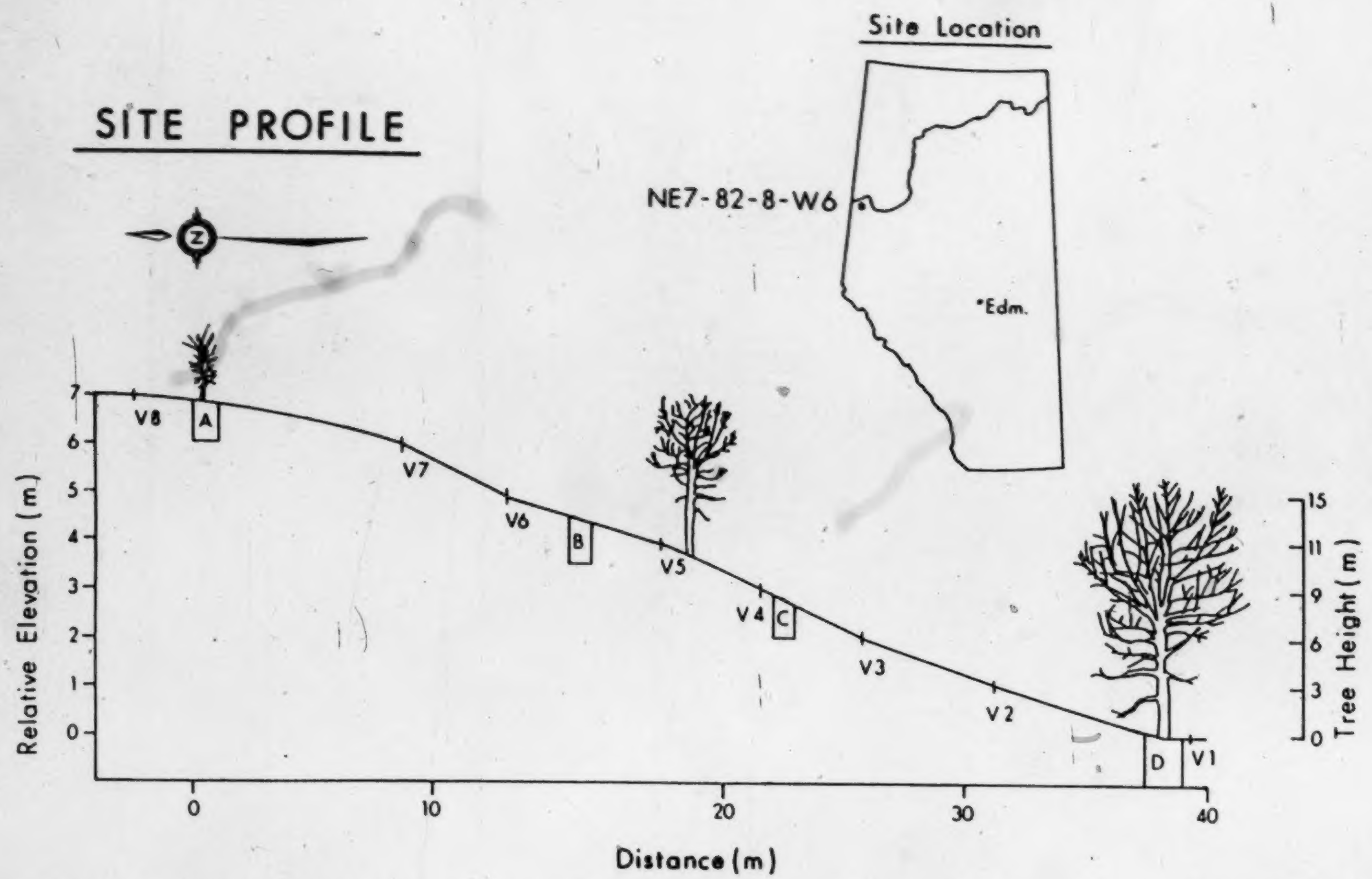
SITE PROFILE
Site Location
NE7-82-8-W6
•Edm.
Relative Elevation (m)
7
6
5
4
3
2
1
0
V8
A
V7
V6
B
V5
V4
C
V3
V2
D
V1
0
10
20
30
40
Distance (m)
Tree Height (m)
15
11
9
6
3
0

FIGURE 3. Site location and slope profile description, showing location of sampling pits along catenary sequence, relative tree growth, and location of vegetation transect lines.

Four soil pits were located along the slope and formed the catenary sequence. The pits were located to represent the changes in apparent growth conditions along the slope. Sample pit location is illustrated in Figure 3. Soil profile descriptions are presented in Tables 1, 2, 3, and 4. Soil pit A is located in a relatively unhealthy plant community, where aspen poplar appears stunted and deformed. Ground cover is sparse and no shrubs grow at this location. The overall appearance is one of bare ground with dying aspen trees. Occasional paper birch (Betula papyrifera) observed at this location appear to be healthier than the aspen, with no visible deformation

Site B retains some of the features associated with site A, but shrub species such as thinleaf alder (Alnus crispa) are present. Leaf litter covers the ground, although herbaceous species are not abundant. This site represents a transition zone between the extremely unthrifty upslope site, and a reasonably productive lower slope position. It also marks the limit to which paper birch extends down the slope. Aspen poplar growing in this location are severely inhibited.

Site C represents another transition area characterized by good productivity, and ground cover species occupying a significant portion of the ground surface. While growth appears unrestricted, the codominant aspen trees are suffering partial top dieback, which is the only obvious difference in the vegetation between this site and site D.

Site D is located near the bottom of the slope and has approximately equal ground surface area of herbaceous species and leaf litter. The shrub layer of thinleaf alder is well developed and some layering of the herbaceous component into different levels is also observed. Tree growth of aspen poplar, the only tree species in the vicinity, appears unrestricted.

TABLE 1. Profile Description: Site A.

SAMPLE NO.	HORIZON	DEPTH (cm)	DESCRIPTION
	L	2 - 0	Undecomposed leaf litter.
A1	Ahe	0 - 4	Yellowish brown (10YR 5/6m); silty clay; strong, fine granular; friable; abundant, fine and very fine, random roots; clear, smooth boundary.
A2	Btfj1	4 - 26	Brown (7.5YR 4/6m); heavy clay; strong, fine subangular blocky; firm; abundant, medium, oblique to horizontal roots; gradual, wavy boundary.
A3	Btfj2	26 - 43	Reddish brown (5YR 4/6m); heavy clay; strong, fine subangular blocky; friable; abundant, medium, horizontal roots; abrupt, wavy boundary.
A4	BC	43 - 58	Dark grayish yellow (2.5Y 5/2m); silty clay; few, fine, prominant, bright reddish brown (5YR 5/6) mottles; weak to moderate, medium subangular blocky; firm; few, fine roots; gradual, wavy boundary.
A5	C1	58 - 75	Yellowish gray (2.5Y 5/1m); silty clay; massive; firm; no roots; gradual, wavy boundary.
A6	C2	75 - 95	Yellowish gray (2.5Y 4/1m); silty clay; massive; firm; no roots; clear, wavy boundary.
A7	C3	95 - 110	Yellowish gray (2.5Y 4/1m); silty clay; common, medium, prominant, pale yellow (5Y 8/4) soft powdery concretions and lamellae; massive; firm; no roots.

TABLE 2. Profile Description: Site B.

SAMPLE NO.	HORIZON	DEPTH (cm)	DESCRIPTION
	L	2 - 0	Undecomposed leaf litter.
B1	Ahe	0 - 4	Brown (7.5YR 4/4m); heavy clay; strong, fine granular; friable; abundant, very fine and fine, random roots;clear, smooth boundary.
B2	Btfj1	4 - 18	Brown (7.5YR 4/6m); heavy clay; strong, fine subangular blocky; firm; abundant medium, few coarse, horizontal roots; gradual, wavy boundary.
B3	Btfj2	18 - 36	Reddish brown (5YR 4/6m); heavy clay; strong, fine subangular blocky; firm; abundant, medium, horizontal roots; abrupt, wavy boundary.
B4	BC	36 - 55	Yellowish gray(2.5Y 5/1m); silty clay; many, medium, prominant, reddish brown (5YR 4/6) mottles; weak, fine subangular blocky; firm; plentiful, medium, oblique, roots; gradual, wavy boundary.
B5	C1	55 - 75	Yellowish gray (2.5Y 4/1m); silty clay; common, medium, prominant, yellowish brown (10YR 5/6) mottles; common, medium, prominant, pale yellow (2.5Y 8/4) soft powdery concretions and lamellae; massive; firm; no roots; diffuse boundary.
B6	C2	75 - 95	Yellowish gray (2.5Y 5/1m); silty clay; common, medium, prominant, bright brown (7.5YR 5/6) mottles; common, medium, prominant, pale yellow (2.5Y 8/4) soft powdery concretions and lamellae; massive; firm; no roots; diffuse boundary.
B7	C3	95 - 105	Yellowish gray (2.5Y 4/1m); silty clay; common, medium, prominant, orange (7.5YR 6/6) mottles; common, medium, prominant, pale yellow (2.5Y 8/4) soft powdery concretions and lamellae; massive; firm; no roots; diffuse boundary.

TABLE 3. Profile Description: Site C.

SAMPLE NO.	HORIZON	DEPTH (cm)	DESCRIPTION
	L-F	5 - 0	Fibrous leaf litter.
C1	Ahe	0 - 5	Brown (7.5YR 4/4m); silty clay; strong, fine granular; very friable; abundant, very fine and fine, random roots; clear, smooth boundary.
C2	Btfj1	5 - 15	Brown (7.5YR 4/4m); heavy clay; strong, fine subangular blocky; friable; abundant, medium, oblque roots; clear, wavy boundary.
C3	Btfj2	15 - 30	Brown (7.5YR 4/6m); heavy clay; strong, fine subangular blocky; firm; abundant, medium and coarse, oblique roots; clear, wavy boundary.
C4	Btfj3	30 - 50	Reddish brown (5YR 4/6m); heavy clay; strong, fine and medium subangular blocky; firm; abundant, medium, oblique roots; clear, wavy boundary.
C5	BC	50 - 65	Yellowish gray (2.5Y 5/1m); heavy clay; many, medium, prominant, brown (7.5YR 4/6) mottles; weak, fine subangular blocky; firm; plentiful medium, few coarse, oblique roots; clear, wavy boundary.
C6	C1	65 - 80	Yellowish gray (2.5Y 5/1m); silty clay; few, medium, prominant, dull brown (7.5YR 5/4) mottles; amorphous; firm; few, medium, oblique roots; gradual, wavy boundary.
C7	C2	80 - 105	Yellowish gray (2.5Y 4/1m); silty clay; few, medium, prominant, pale yellow (2.5Y 8/4) soft powdery concretions and lamellae; amorphous; firm; no roots.

TABLE 4: Profile Description: Site D.

SAMPLE NO.	HORIZON	DEPTH (cm)	DESCRIPTION
	L-F-H	7 - 0	Humified and fibrous leaf litter.
D1	IAhe	0 - 6	Dark brown (7.5YR 3/4m); silty clay loam; moderate, medium granular; very friable; plentiful, fine, random roots; clear, smooth boundary.
D2	IBtfj1	6 - 16	Brown (7.5YR 4/4m); silty clay loam; moderate, medium granular; very friable; abundant, medium, oblique roots; diffuse, wavy boundary.
D3	IBtfj2	16 - 27	Brown (7.5YR 4/4m); silty clay; strong, fine subangular blocky; friable; abundant, medium, oblique roots; clear, wavy boundary.
D4	IIBtfj	27 - 40	Brown (7.5YR 4/4m); silty clay; strong, fine subangular blocky; firm; abundant, medium, oblique roots; abrupt, wavy boundary.
D5	IIBC	40 - 60	Dull yellowish brown (10YR 5/3m); silty clay; moderate, medium subangular blocky; firm; abundant, medium, oblique roots; clear, wavy boundary.
D6	IIC1	60 - 83	Dark grayish yellow (2.5Y 4/2m); silty clay; massive; firm; few, medium, oblique roots; clear, wavy boundary.
D7	IIC2	83 - 100	Yellowish gray (2.5Y 4/1); silty clay; common, fine, prominant pale yellow (2.5Y 8/4) soft powdery concretions and lamellae; massive; firm; few, fine, oblique roots.

4.3 FIELD SAMPLING

4.3.1 SOIL SAMPLING

Seven 3 kg samples were collected from each soil pit according to major soil horizons, to a depth of approximately 1 m. Bulk density cores were extracted with a Uhland corer at various depths by pounding the corer into the side of the soil pits. Samples for moisture determinations were collected on three dates. Bulk samples for the growth experiment were collected from the A, C, and D pits at two depths (surface and 35 cm). Thin section samples were removed from the A, C and D pits using aluminum boxes. Surface samples were collected in large boxes and a small box was used to extract one sample from 35 cm depth.

4.2.2 VEGETATION SAMPLING

Species composition and tree size data were collected from the field site. Ground cover species were studied using a quadrat method where five 1 m^2 quadrats were located along a transect line representing 1 m increments in slope elevation. The transects were laid out using a clinometer, following a compass line at right angles to the slope contour. The transect lines were designated as V1 to V8, and are illustrated in Figure 3. Each point where the transect line intersected the layout line was designated Q3 and was considered to be the center of the transect line. Two quadrats were then located along the contour line on each side of the Q3, giving five quadrats per transect line times eight lines equals 40 quadrats. The sampling method for each quadrat involved dividing the quadrat into four 2500 cm^2 quarters and the cover percent within the quarter estimated for each species, bare ground, lichens and mosses, or leaf litter.

Aspen tree heights were measured by triangulation for three codominant trees in three slope positions (A,BC,D). One sample tree from each slope position was selected and stem sections were prepared at stump height for dendrochronolgy. Leaves and twigs were collected from midcrown positions on sample trees in August and these, along with wood and bark from the stem sections were used for elemental analysis.

4.4 LABORATORY MEASUREMENTS

4.4.1 SOIL

After air drying, 28 soil samples (4 pits * 7 depths) were ground with a mortar and pestle to pass a 2 mm seive. The ground samples were stored in sealer jars for use in the following analyses:

ANALYSIS	METHOD	REFERENCE
pH	$CaCl_2$and H_2O	McKeague (1981), p 66
PARTICLE SIZE DIST.	Sedimentation	Day (1965).
TOTAL C.E.C.	NaOAc	McKeague (1981), p. 82.
EXCH. CATIONS	NH_4OAc (pH 7)	McKeague (1981), p. 78.
EXCH. CATIONS	NH_4OAc (pH 4.8)	McKeague (1981), p. 78.
EXCH. ACIDITY	KCl	Thomas (1982).
EXCH. ACIDITY	$Ba(Ac)_2$	Pawluk (1978).
EXTRACTABLE FE,AL	Dith Cit Bicarb	McKeague (1981), p. 98.
EXTRACTABLE FE,AL	Oxalate	McKeague (1981), p. 103.
EXTRACTABLE FE,AL	Pyrophosphate	McKeague (1981), p. 104.
TOTAL CARBON	Leco furnace	McKeague (1981), p. 109.
TOTAL NITROGEN	Kjeldahl	McKeague (1981), p. 129.
AVAIL. PHOSPHORUS	Med. Bray (mod)	McKeague (1981), p. 175.
TOTAL ELEMENTAL	I.N.A.A.	Helmke (1982).
MOISTURE RETENTION	Pressure plate	McKeague (1981), p. 45.

Clay mineralogy was investigated by Xray diffraction using the following 7 pretreatments (Dudas and Pawluk, 1982):

1. CALCIUM SATURATED.......54% R.H.
2. CALCIUM SATURATED.......ethylene glycol solvated.
3. CALCIUM SATURATED.......glycerol solvated.
4. POTASSIUM SATURATED.....54% R.H.
5. POTASSIUM SATURATED.....100° C.
6. POTASSIUM SATURATED.....300° C.
7. POTASSIUM SATURATED.....550° C.

Thin sections were prepared by impregnation under vacuum, mounting on a glass slide and polishing to 30 micrometers. These are standard preparation procedures at the University of Alberta.

4.4.2 VEGETATION

Aspen tree samples were divided into leaves, petioles, twigs, heartwood, midwood, and sapwood. The determination of elemental content of the various tissues was carried out according to the (dry ash) method described in Isaac and Kerber (1971).

4.5 GREENHOUSE EXPERIMENT

This experiment was designed to distiguish the effects of soil physical properties (bulk density, moisture retention characteristics) from soil chemical factors. Surface and subsurface samples were collected from the A, C, and D pits. They were air dried and passed through a 5 mm seive with a minimum of grinding. Quartz sand ~~was~~ mixed with the soil samples in a 1:3 w/w proportion to form composite samples of similar overall particle size distribution and Db. These composites were added to 1 l closed bottom pots. Soil composites were dressed with 25 g of air dry peat, smoothed and levelled, and a light layer of fine sand was placed on top to aid germination. Ten aspen seeds were germinated per pot. Aspen seeds were collected from the University of Alberta Botanical Garden at Devon. Young seedling mortality necessitated several transplants but an effort was made to maintain at least 3 seedlings per pot. All pots were watered on a consistent basis and the trees were grown for 20 weeks. Seedlings were harvested by cutting the tops, measuring shoot length and drying tops for elemental analysis. Tree roots were washed from the soil and weighed.

In a separate experiment, 10 wheat seeds of two varieties were added to each of 4 pots, including the following treatments:

A surface   A subsurface   D surface   D subsurface

The two varieties used were Scout, an aluminum sensitive cultivar, and Atlas, an aluminum tolerant cultivar (Foy and Taylor, 1985). At harvest, after 10 weeks, the tops were clipped at soil level and the roots washed from the soil. Measurements of the root to shoot length and weight were made after drying at 60 °C for 48 hours. These samples were then analysed for elemental content.

5. RESULTS

5.1 SOIL PHYSICAL PROPERTIES

5.1.1 Particle Size Analysis

Figure 4 shows the particle size distribution for profiles A and D. The high clay content of these soils is typical for soils derived from shale parent materials. Clay content of the C horizons is similar to results from other studies of the Boundary complex such as 58% (Pawluk, 1971), 58% (Clark and Green, 1964), and 57% (Pawluk and Dudas, 1978). As shown in Table 5, the particle size distributions of profiles B and C are similar to profile A. A different trend is apparent in profile D.

The particle size distribution of profile A reflects the importance of lessivage as a soil forming process in this catenary sequence. The clay content at 20 cm depth is sufficient to classify this horizon as a Bt (Canada Soil Survey Commitee, 1978). The clay content of profiles B and C reflect the occurrence of similar processes.

Profile D is affected by a combination of processes. While this profile is also affected by illuviation of clays, the enrichment of coarser fractions in the surface horizons has a dominant influence on particle size distribution and other properties of this soil. The lithological discontinuity observed at approximately 30 cm depth in profile D is attributed to the accumulation of glacial debris in depressional areas. At the time of deglaciation, a thin veneer of glacial till was deposited over the entire area. Subsequent downslope movement of this coarser textured glacial material caused by mass wasting and suspension in runoff waters has resulted in accumulation in lower slope positions. This material is mineralogically different from the shale material and greatly affects soil properties in profile D. A similar feature was observed by Pawluk and Dudas (1978) for a profile of Boundary soil.

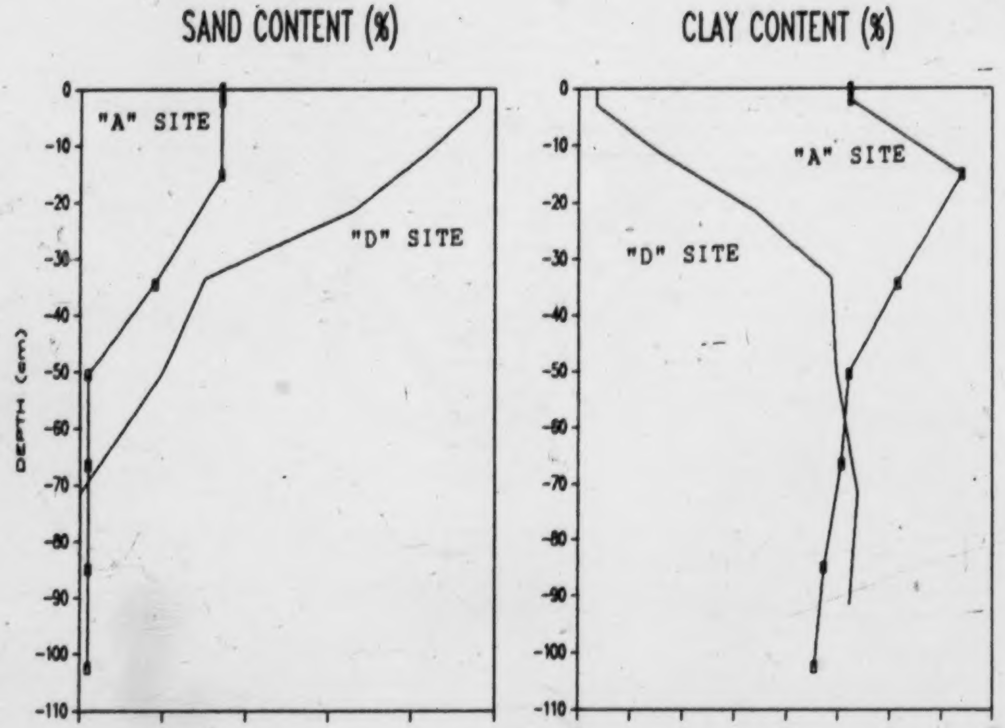

Figure 4. Particle size distribution for profiles A and D, showing the illuvial Bt horizon in profile A, and the lack of such a dominant feature in profile D.

TABLE 5. Particle size distribution of samples from profiles B and C.

	DEPTH (cm)	%SAND	%SILT	%CLAY
B1	-2.0	2.4	37.6	60.0
B2	-11.0	0.3	30.5	69.2
B3	-27.0	0.1	32.8	67.1
B4	-45.5	0.1	40.2	59.7
B5	-65.0	0.1	42.8	57.1
B6	-85.0	0.0	44.6	55.1
B7	-100.0	0.1	45.8	54.1
C1	-2.5	2.4	44.1	53.5
C2	-10.0	1.2	38.7	60.1
C3	-22.5	0.3	32.1	67.6
C4	-40.0	0.1	32.8	67.1
C5	-57.5	0.1	39.5	60.4
C6	-72.5	0.0	43.6	56.4
C7	-92.5	0.0	45.5	54.5

5.1.2 BULK DENSITY

Bulk density measurements taken during two separate sampling trips were averaged and are presented in Table 6. The bulk density of soil materials in the lower solum is similar for profiles A and D. There is a general increase in bulk density with depth, which is typical for soils. The higher bulk density for the upper portions of profile D may be related to the coarser texture of the surface horizons. Sandy soils tend to have higher bulk density than clay soils (Russell, 1973). The difference in bulk density may also relate to greater natural compaction of soil materials resulting from higher moisture content in lower slope positions. Higher moisture contents increase soil compaction because of a lubricating effect which allows individual particles to slide past one another and become oriented when stress is applied. In addition, soil pit D is located near several large trees and core samples removed in close proximity to large tree roots may be affected by root volume compression. This would result in a skewed sample since the lower density tree roots were excluded.

Bulk density does not appear to restrict root proliferation in profile A, and thus is not considered a causal factor in the observed growth differences between upslope and downslope sites.

5.1.3 MOISTURE RETENTION CHARACTERISTICS

Results of pressure plate analysis for samples from profiles B and C are presented in Table 7. Changes in the relationship between moisture content and moisture potential for the various samples are closely related to the clay content. Moisture content at 1500 kPa is highest for samples B2 (69.2 % clay), B3 (67.1 % clay), and C3 (67.6 % clay). Equations of capillarity can be used to estimate the effective diameter of pores which will be drained at a certain moisture potential. An effective pore diameter of 0.0001 mm will be drained by a tension of 1500 kPa (Marshall and Holmes, 1979), while 33 kPa will drain pores with an effective diameter larger than 0.005 mm. For this reason, the moisture content of a soil material at 33

TABLE 6. Average bulk density (Mg/m3) at various depths for upper (A) and lower (D) slope positions.

	PROFILE "A"	PROFILE "D"
SURFACE	0.85	0.91
18 cm	1.15	1.38
37 cm	1.24	1.36
67 cm	1.41	1.40

TABLE 7. Moisture content (%) of disturbed samples from profiles B and C using pressure plate at 33, 100, 800 and 1500 kPa.

	33 kPa	100 kPa	800 kPa	1500 kPa
B1	33.3	29.6	22.0	20.5
B2	35.3	31.5	25.3	23.1
B3	34.6	32.3	24.2	22.5
B4	32.6	28.4	21.8	20.2
B5	32.9	28.5	21.4	19.5
B6	33.0	28.3	21.5	N.D.
B7	33.7	29.2	21.9	19.8
C1	31.0	29.7	21.9	19.7
C2	34.4	33.6	24.8	23.0
C3	36.0	35.7	25.0	23.5
C4	35.5	35.4	24.8	23.0
C5	34.1	32.3	22.4	20.6
C6	32.1	30.7	20.7	18.8
C7	32.5	31.0	20.9	18.9

kPa is controlled primarily by soil structure, while moisture content at 1500 kPa is controlled primarily by soil texture (Hillel, 1982). Since structure of samples used for pressure plate analysis is disturbed, the 33 kPa moisture content may not closely reflect field conditions. The 1500 kPa moisture content, however, is expected to describe natural systems more accurately.

Changes in moisture retention characteristics within the range considered to be available for plants are illustrated for profiles A and D in Figure 5. The different patterns of moisture availability for these two profiles reflect their different particle size distributions. Profile A is similar to profiles B and C, with accumulations of clay in Bt horizons resulting in a rather narrow range of available moisture, with a large water storage capacity in small pores which plants cannot exploit. Profile D, particularly in surface horizons has a much wider range of available moisture. The differences are most noticeable at 1500 kPa moisture tension, which is primarily a function of soil texture.

5.1.4 FIELD MOISTURE CONTENT

Figure 5 compares field moisture determinations taken in May and August, 1985 with available soil moisture values for profiles A and D. A reduction in moisture content occurred for all depths during the summer months. In the A profile, the zone of maximum depletion was at 20 to 40 cm. The moisture content in this depth range during August reflects a water tension of 1500 kPa, which is considered to be the highest tension extractable by plants. This portion of the profile is the zone of most active water uptake. Examination of the results for the D profile indicate that maximum water uptake occurs at a depth of 50 to 70 cm, although the maximum water tension is still less than 1500 kPa in this depth range during August.

The zone of maximum water depletion reflects the concentration of active plant roots in the solum. The 20 to 40 cm depth of this zone in the A profile graphically illustrates the inhibition of root penetration in the lower portions of this profile. The convergence of

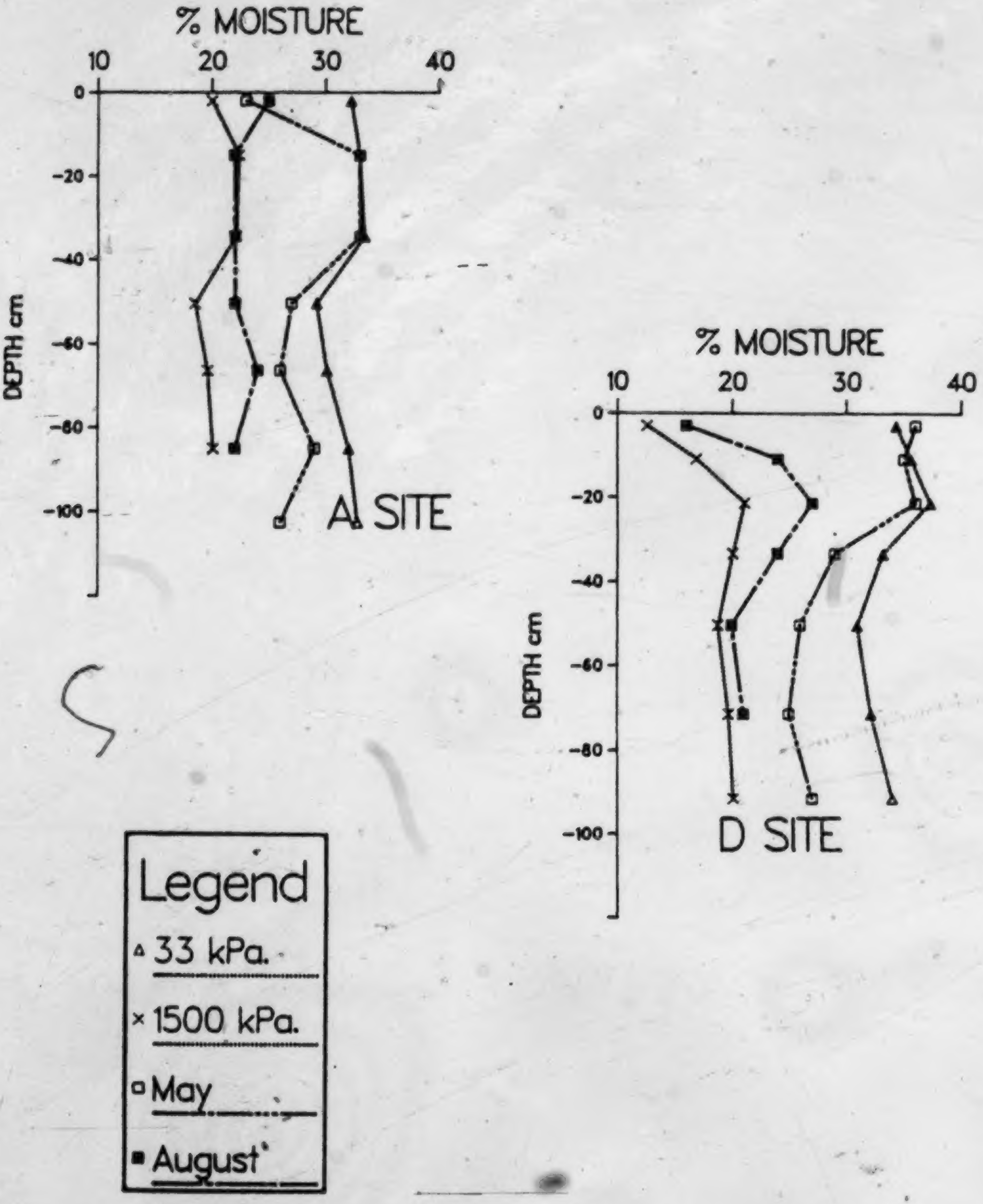

FIGURE 5. Field moisture content of catena soils during the 1985 growing season. Depletion of subsoil moisture occurs primarily as a function of plant root extraction. The shallow zone of maximum root uptake reflects inhibited root development in profile A.

the May and August moisture curves below this depth indicates a lack of plant water uptake. The lack of water uptake from lower depths constrains plant growth during periods of drought. Since growth of aspen poplar is very sensitive to soil moisture status (Sucoff, 1982), this provides a possible explanation for the poor growth response in upper slope positions. The consistent moisture extraction with depth for the D profile indicates that root proliferation into lower soil horizons is not limiting to plant growth in this slope position. In addition, site D is wetter than site A, by virtue of downslope drainage and interflow during the summer months. These two factors preclude the likelihood of water stress in lower slope positions.

5.1.5 MICROMORPHOLOGY

A visual interpretation of soil processes can be derived from the study of micromorphology. Observation of soil microstructure provides insight into the spatial arrangement of plant roots, soil minerals, aggregates and voids, providing a window on the plant root environment. Alteration of soil parent materials by physical, chemical and biological processes results in recognizable features and the relative effects of competing processes of soil formation can often be estimated by interpretation of thin sections.

Plate 1 illustrates some features of the micromorphology of profiles A, C and D. Fabric types and a description of features observed in thin sections from profiles A and D are presented in Table 8. Profile A has a very similar fabric to the Boundary soil profile described by Pawluk and Dudas (1978) from the Grimshaw area. Fabric types observed at the surface are mullgranic and granoidic - metafragmoidic while lower in the solum a fragmoidic fabric is dominant. The development of granic fabric is discussed by Pawluk and Dudas (1978) and is attributed primarily to biological activity. Coalescence of granic units into larger F members leads to the formation of granoidic fabric with a system of interconnected vughs providing pathways for gas exchange and water infiltration. The

PLATE I. Micromorphological features of profiles A, C and D. (a) surface sample of profile A illustrates granoidic - metafragmoidic fabric depicting early stage of alteration of shale parent material; (b) fragmic fabric characteristic of unaltered shale parent material; (c) profile C surface horizon with granoidic - metafragmoidic fabric; (d) subsurface sample from profile C with granoidic - metfragmoidic porphyric fabric similar to surface of profile A; (e) maximum expression of granoidic - porphyric fabric in Boundary soil reflecting extensive biological alteration of soil materials in surface sample from profile D; (f) porphyric fabric from subsurface of profile D.

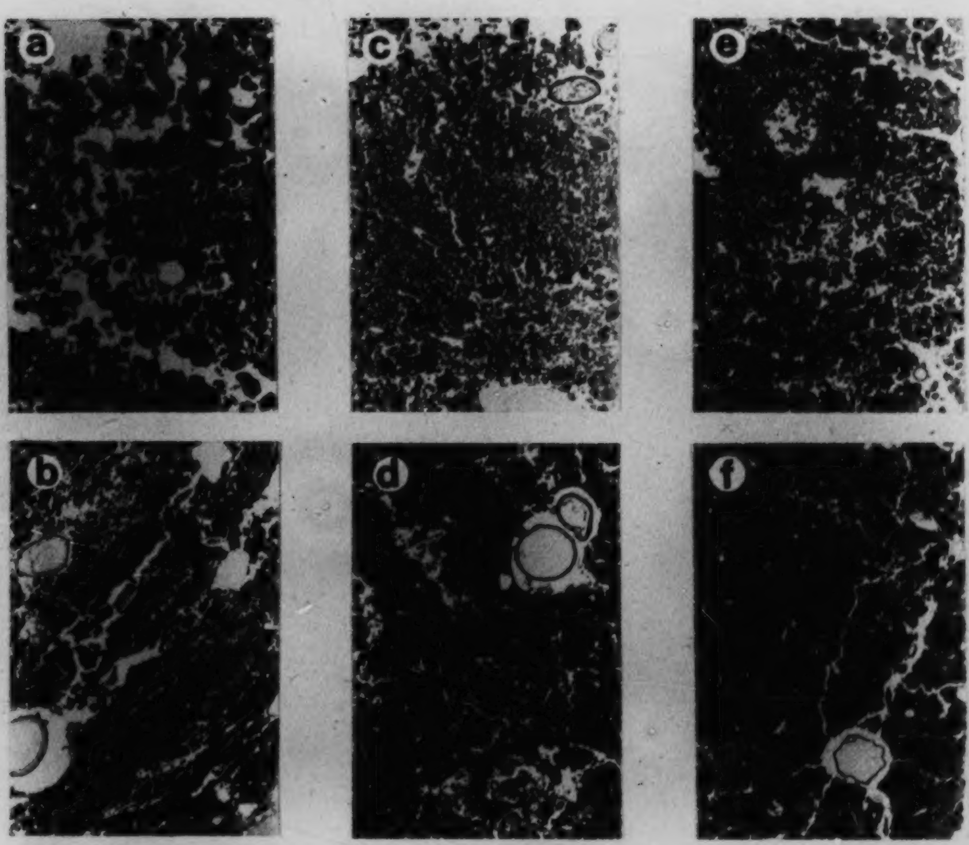
a
c
e
b
d
f

TABLE 8. Micromorphological features of upper solum for profile A.

HORIZON (DEPTH cm)	FABRIC TYPE	DOMINANT PLASMIC FABRIC	REMARKS
Ahe (0 - 4)	granoidic - metafragmoidic	vo - masepic	common neoargillans occaisional neoferrans and quasiferrans
Btfjl (4 - 8)	granoidic - metafragmoidic	vo - masepic	common neoargillans and quasiargillans occaisional goethite nodules
(8 - 12)	granic// granoidic - metafragmoidic	vo - masepic	frequent discrete goethite nodules common diffuse sesquioxidic nodules occaisional jarositans
(12 - 16)	granoidic - metafragmoidic	clinobimasepic	common diffuse sesquioxidic nodules common discrete goethite nodules
(16 - 20)	matrigranoidic// fragmoidic	clinobimasepic	matrigranoidic areas: common neoferrans and quasiferrans fragmoidic areas: channel ferrans and neoferrans common neojarositans and neoargillans
(21 - 27)	fragmic - fragmoidic// granoidic	omnisepic and bimasepic	abundant void argillans common goethite nodules
Btfjl (27 - 35)	fragmic - fragmoidic// granoidic	omnisepic (unistrial) and masepic	common void argillans neoargillans void ferrans

TABLE 8 cont. Micromorphological features of upper solum for profile D.

HORIZON (DEPTH cm)	FABRIC TYPE	DOMINANT PLASMIC FABRIC	REMARKS
IAhe (0 - 6)	vughy porphyric granoidic - porphyric	vo - insepic	isotropic organic F clasts abundant discrete goethite nodules normal sesquioxidic nodules channel argillans
IBtfj1 (10 - 16)	granoidic - porphyric	vo - ma - insepic	highly interconnected metavughs abundant goethite nodules common sesquioxidic nodules rare void argillans
IBtfj2 (16 -20)	granoidic - porphyric	skel - vo - insepic	highly interconnected orthovughs common sesquioxidic nodules occaisional void argillans and papules
(20 - 27)	vughy porphyric	skel - insepic	rare void argillans
IIBtfj (27 - 35)	vughy porphyric	vo - insepic	common void argillans, occaisional neoargillans

fragmoidic fabric is a feature of the sedimentary parent material, with joint planes and craze planes developing from wetting and drying cycles. The fragmoidic fabric type, therefore indicates that plant roots and soil organisms have not significantly altered the structure of the shaly parent material. The 20 to 30 cm depth range is characterized by discrete pockets of the two major fabric types. Each pocket often has a diameter in thin section of 10 cm or less. The fragmoidic type has neojarositans associated with F members, and the matrix often appears as a drab gray color in reflected light. The granic and granoidic regions are characterized by infusions of sesquioxides occurring as ferrans, neoferrans, and quasiferrans which provide various degrees of red coloration. The highest concentrations of these features are usually found adjacent to voids and appear to be associated with the more extensively reorganized granoidic units.

The micromorphology of profile D, reflects pedogenic processes of a different nature than the upper slope positions. The granoidic porphyric fabric in surface horizons is a result of extensive reorganization of soil materials with continuous comminution of organic materials and mixing of organic and mineral components. There is a fairly uniform distribution of Fe oxides as nodules in this profile, and the bands and infusions observed in profile A are absent. Features of the shale parent materials are absent. Brewer (1976) attributes the formation of smoothed vughs to faunal activity. The insepic plasmic fabric observed in surface horizons has been considered as an inherited feature (Pawluk and Dudas, 1978).

The presence of void argillans in the 20 to 35 cm depth range for profile D provides the necessary evidence to designate this as a Bt horizon. The large increases in clay content with depth in this profile cannot be attributed to illuviation, however, since argillan development was not extensive. Changes in clay content between the surface and 35 cm depth in this profile are attributed to the mixing of transported glacial debris with the shale material, as was discussed previously.

Profile C displays features in common with profiles A and D. The granic / granoidic - metafragmoidic fabric which occurs in the surface horizons of profile A is found at approximately 35 cm depth in profile C, while the vughy porphyric fabric associated with profile D is also observed in the surface of profile C. This suggests that a transition occurs from the granic / granoidic fabric to the vughy porphyric fabric as soil development proceeds in this catena. The effects of plant roots and the associated soil flora and fauna are probably the main agents of this change.

The effects of the observed micromorphological features on plant growth, and the extent to which poor growth in upper slope positions is caused by structural factors are considered to be minor. There is an obvious relationship between areas of poor root penetration and the presence of fragmic units of unaltered shale parent material in upper slope positions. The improved root penetration and growth response of trees in lower slope positions is accompanied by granoidic porphyric and vughy porphyric fabric. However, since the features observed in the D site (fabric type and plasmic fabric) are interpreted by Pawluk and Dudas (1978) and Brewer (1976) to be derived from biological activity, these structures are likely the result of improved root growth, rather than the cause of it.

5.2 CLAY MINERALOGY

X-ray diffractograms of samples from profile A indicate that the composition of the clay mineral suite is an admixture of mica, hydrous mica, and kaolinite. A similar mineralogical composition was found by Pawluk and Dudas (1978) for the profile near Grimshaw.

In sample A1 (Fig. 6), the presence of hydrous mica is indicated by the broad reflection centered on 1.2 nm for the Ca-54 treatment. The minor extent of rehydration for K-54 treatments is indicated by a slight broadening of the base of the 1.0 nm mica peak. This very limited rehydration and a very weak 1.7 nm reflection for the Ca-EG treatment is the only evidence of smectite in this sample. The expanding clay present therefore, is primarily hydrous mica, showing

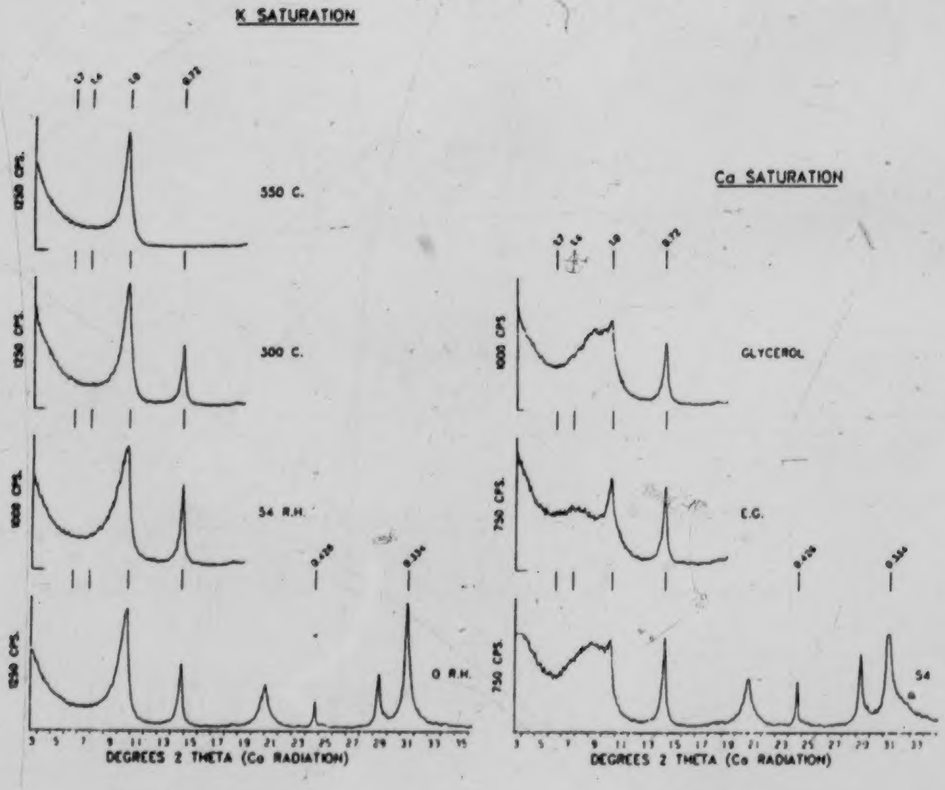

FIGURE 6. Xray diffraction patterns for clay fraction from sample A1.

a range of moderate to nearly complete depotassification. Unaltered mica is indicated by the strong peak at 1.0 nm in all diffractograms, and the second order peak at 0.50 nm indicates that the mica includes dioctahedral (ie. muscovite) species. Kaolinite is represented by the 0.72 nm reflection and a second order peak at 0.36 nm. Quartz is also present in this sample, showing peaks at 0.426 and 0.334 nm.

Figure 7 displays the Ca-54 treatments for samples A2 through A7, providing insight into the changes in mineralogy with depth in this profile. Sample A2 is from the Bt horizon and shows a very similar X-ray diffraction behaviour to sample A1. The increased intensity of the 1.5 nm peak indicates a high degree of depotassification of the hydrous mica in this sample. Sample A3 shows a slightly different behaviour, as the well defined peak at 1.5 nm in A2 is not present in A3, and only a broad sloping base to the 1,0 nm mica peak is observed. Sample A4 has a similar diffractogram to A2 with reflections at 1.2 and 1.5 nm. Jarosite is also visible in this sample and is represented by a strong reflection at 0.507 nm with weaker peaks at 5.66 to 5.71, 3.11 to 3.13, and 3.06 to 3.08 nm indicating a solid solution between jarosite and natrojarosite (Ross et al., 1982). The jarosite peak at 0.507 nm appears as a doubling of the 0.500 nm mica peak and can be seen in almost every sample from the catena, indicating trace amounts of jarosite are present in surface samples of the profiles.

Samples A5, A6 and A7 are characterised by broad, relatively weak reflections over the range of 1.2 to 1.5 nm which indicates the dominance of mica and kaolinite in the lower portions of the profile, with lesser amounts of hydrous mica. Pawluk and Dudas (1978) attributed higher 1.5 nm reflections, higher surface area, higher C.E.C. and lower K_2O content in surface horizons to a higher degree of mica alteration. Although only X-ray data are presented here the results are in general agreement with this hypothesis. It appears that in the A profile, mica is not altered to the extent of the material studied by Pawluk and Dudas (1978) since the 1.4 nm peaks

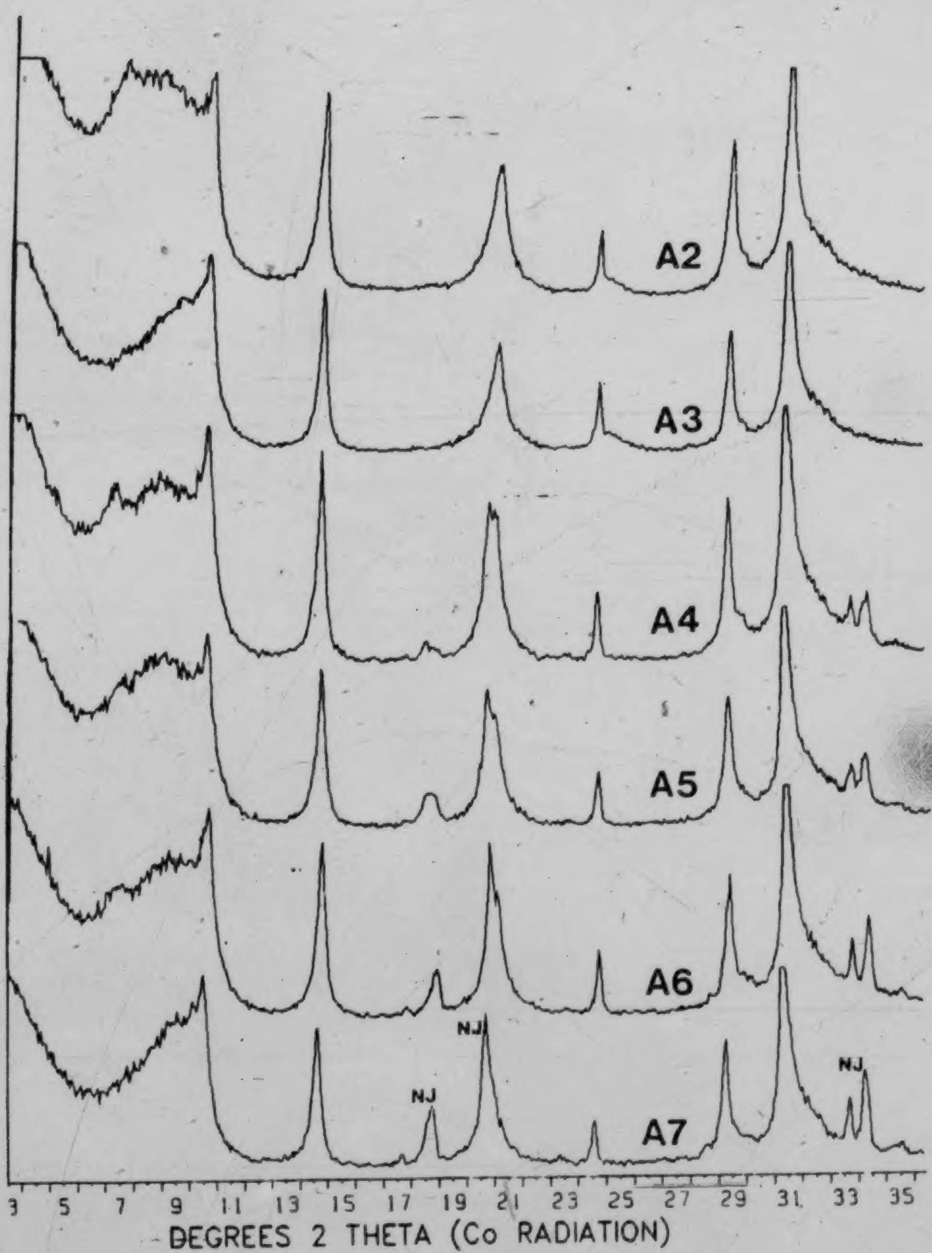

FIGURE 7. Xray diffraction patterns (Ca54 treatment) for clay samples A2 to A7, illustrating increasing intensity of 1.4 nm. reflections in the upper solum. The presence of natrojarosite in samples A4 through A7 is indicated by peaks marked NJ.

(Ca-54 treatment) for sample A1 are not as sharp as those recorded for the C horizon in the previous study.

Profile B has a similar mineralogical composition to profile A. There is more mica depotassification in this profile as indicated by strong reflections at 1.5 nm (Ca-54 treatment) for most samples, and in contrast to profile A, samples from the lower solum have strong 1.5 nm reflections as well. There is a relatively consistent degree of mica alteration at all depths in profile B, with micas showing moderate depotassification. As with profile A, the jarosite reflections get progressively stronger with depth in the profile.

Profile C has essentially the same characteristics as have been described for profiles A and B. There are very minor reductions in the strength of the 1.5 nm reflections with depth in profile C.

For profile D (Figs. 8 and 9), there is a greater degree of complete mica depotassification compared with the profiles from the upslope positions. In sample D1 there is evidence for the presence of partial aluminum hydroxy interlayers as indicated by the broadened base of the 1.0 nm mica peak in the K-0 treatment, and the subsequent expansion of the interlayer region during rehydration (K-54 treatment). This behaviour was also observed for sample D2 (not shown). The presence of aluminum hydroxy interlayers in this profile is favored by the slightly higher pH, which promotes polymerization of Al^{3+}. These aluminum hydroxy polymers prevent the entry of K^+ into the interlayer region, inhibiting fixation reactions and allowing subsequent rehydration. Mineralogically, this profile bears the closest resemblance to the profile studied by Pawluk and Dudas (1978). There is evidence of smectite in the surface samples from this profile, since some rehydration of interlayer positions is indicated for K54 treatments. The loss of the 1.5 nm reflection (Ca-54 treatment) indicates that there is little complete depotassification below the solum.

There is limited variation in X-ray diffraction characteristics of clay separates within profiles and between the profiles of the catena. Hydrous mica in surface horizons is generally more

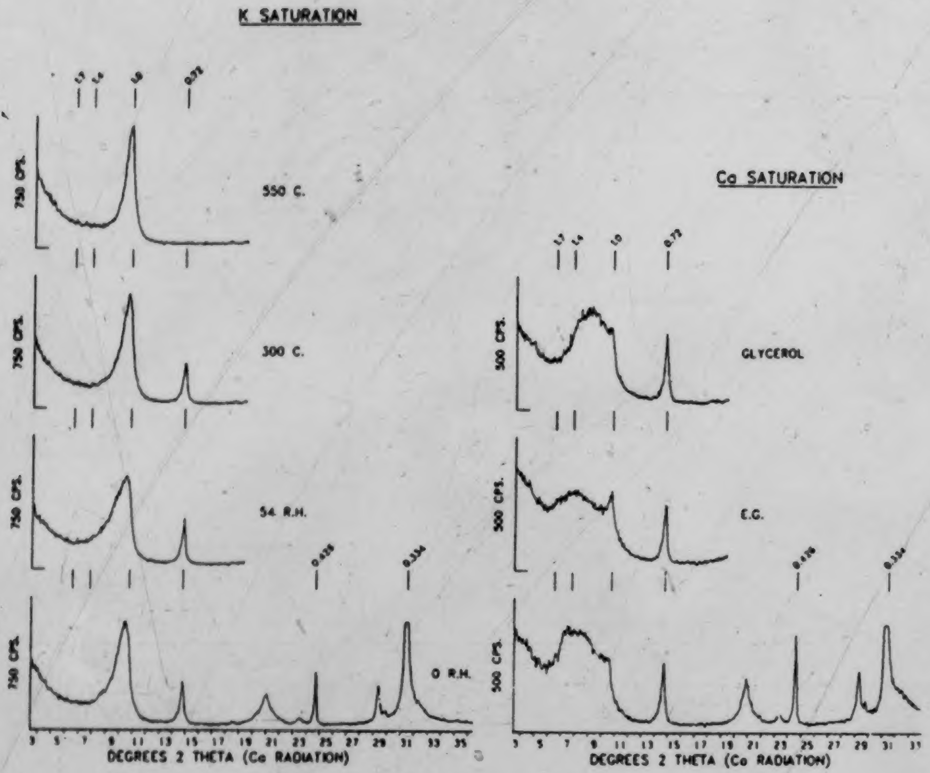

FIGURE 8. Xray diffractograms for clay sample D1.

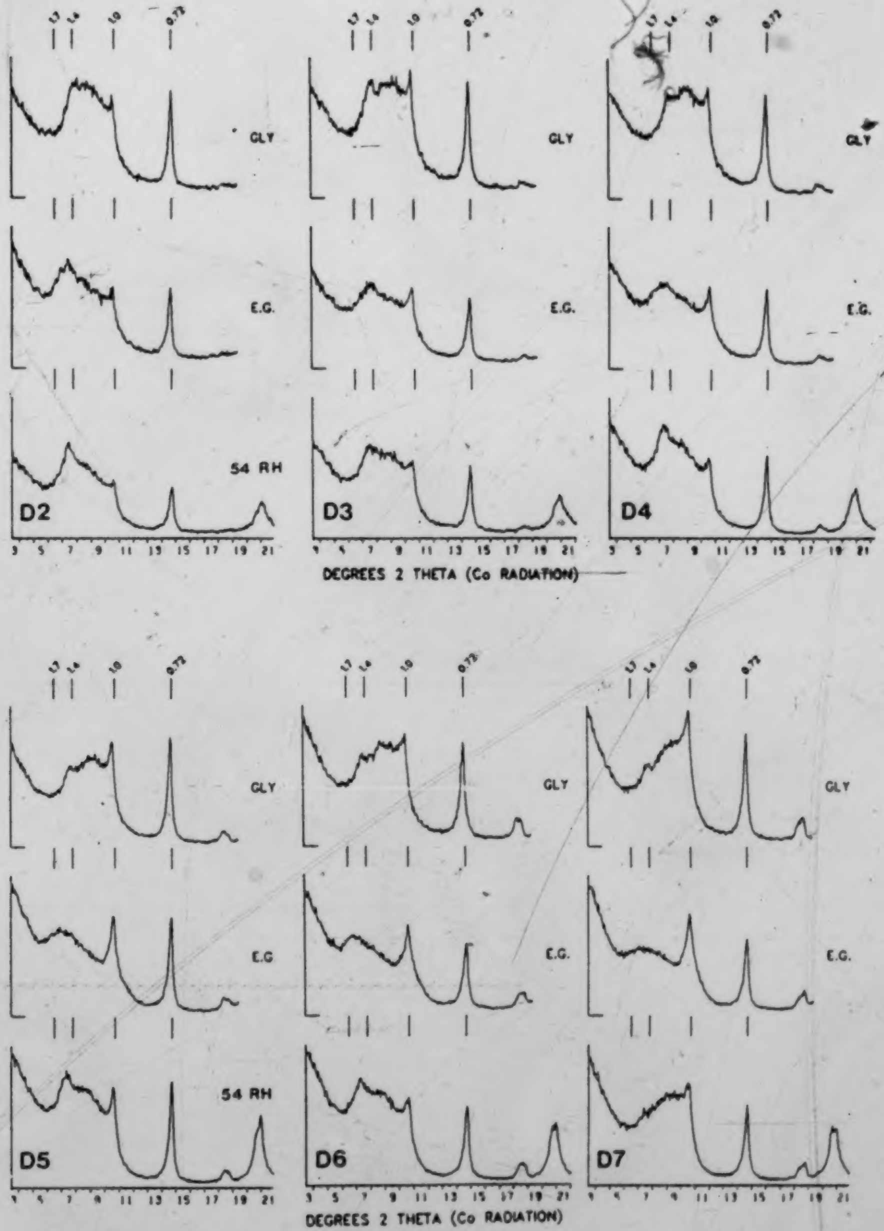

FIGURE 9. Xray diffractograms of Ca treatments for clay samples D2 to D7, illustrating maximum alteration of mica in surface samples and relatively unaltered parent materials in sample D7.

depotassified than in the lower solum. The stability of micaceous minerals in this extremely acidic soil is of interest, however since accelerated depotassification is expected in strongly acidic environments. Maximum alteration of mica in the catena, as indicated by the strength of 1.5 nm reflections in Ca-54 treatments, is observed in profile D. The high degree of depotassification in this more productive site suggests an effect of plant roots on mica weathering. Uptake of K from soil solutions by plant roots may accelerate depotassification of mica in these soils.

The dominance of hydrous mica and mica in the clay mineral fraction distinguishes Boundary soil from inland acid sulfate soils studied in Saskatchewan (Curtin and Mermut, 1985) and Texas (Carson and Dixon, 1983), where smectite is a dominant clay mineral. Study of the clay mineralogy of this catenary sequence has provided insight into plant - soil interactions. The release of K during mica weathering contributes a steady source of this essential plant nutrient. In addition, the presence of aluminum hydroxy interlayers in surface soils from the D site indicates that a subtle difference in aluminum solubility across the catena may prevent aluminum toxicity in lower slope positions.

5.3 CHEMICAL PROPERTIES

The most ubiquitous characteristic of acid sulfate soils is the extremely low pH values which result during oxidation of pyritic parent materials. Soil chemical factors associated with these extremely acid soils are presented in this section.

5.3.1 ACIDITY

The pH values obtained in H_2O are presented in Figure 10, and $CaCl_2$ pH values are presented in Table 9. The difference between the pH in H_2O and in $CaCl_2$ indicates the amount of reserve acidity. The pH value obtained in H_2O describes the active acidity and is more related to solution pH affecting plant roots,

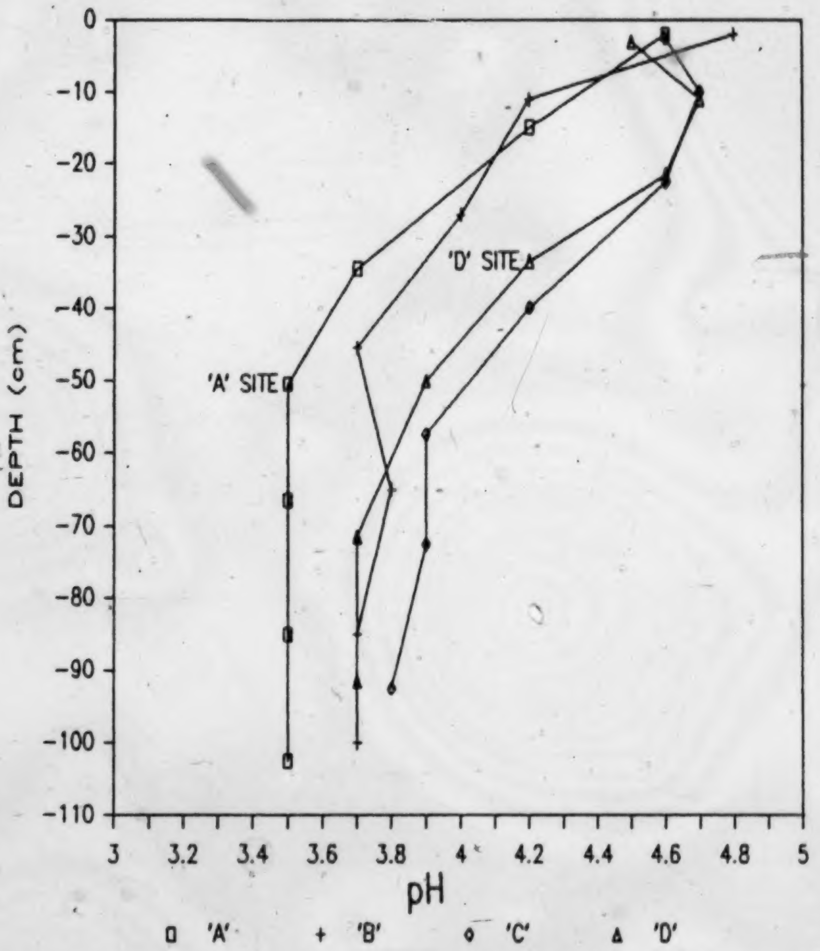

FIGURE 10. pH values (1:1 H_2O) of soil samples from the catena, illustrating the slightly higher pH values of surface samples from the lower slope positions.

TABLE 9. Chemical properties of catena soils.

	pH CaCl2	ORGANIC CARBON %	TOTAL NITROGEN %	EXTRACT. P ppm	EXCHANGEABLE CATIONS Ca	Mg	K	EXCHANGE ACIDITY KCl(Al)	KCl(TOT)	Ba(Ac)2	TOTAL C.E.C.	BASE SATURATION %
					cmol/kg							
A1	3.9	2.38	0.22	7.0	2.9	1.4	1.2	8.0	8.6	13.6	23.5	23.4
A2	3.5	0.83	0.13	1.0	0.1	0.1	0.4	14.6	15.5	17.6	23.2	2.6
A3	3.2	0.50	0.11	1.0	0.0	0.1	0.3	10.2	11.4	14.9	19.1	2.1
A4	3.1	N.D.	0.12	1.0	0.0	0.1	0.3	9.8	11.8	13.6	19.7	2.0
A5	3.1	N.D.	0.12	1.0	0.0	0.1	0.3	10.1	12.6	14.4	18.1	2.2
A6	3.1	N.D.	0.13	2.0	0.0	0.1	0.3	10.0	11.3	13.5	16.7	2.4
A7	3.1	N.D.	0.13	3.0	0.0	0.0	0.3	8.6	10.4	12.2	17.8	1.7
B1	4.0	1.78	0.20	7.0	4.2	2.0	1.5	7.2	7.8	13.0	23.5	32.8
B2	3.7	0.79	0.15	1.0	0.4	0.3	0.6	13.7	14.7	16.1	23.5	5.5
B3	3.5	0.58	0.15	1.0	0.2	0.2	0.6	13.3	14.6	16.5	23.2	4.3
B4	3.4	N.D.	0.14	1.0	0.1	0.1	0.5	12.4	14.0	15.4	22.3	3.1
B5	3.3	N.D.	0.13	1.0	0.0	0.1	0.4	12.1	13.5	14.0	20.4	2.5
B6	3.4	N.D.	0.13	1.0	0.0	0.0	0.4	11.9	13.5	14.9	21.6	1.9
B7	3.3	N.D.	0.19	2.0	0.0	0.0	0.4	11.8	13.7	15.5	21.6	1.9

TABLE 9 cont. Chemical properties of catena soils.

	PH CaCl2	ORGANIC CARBON %	TOTAL NITROGEN %	EXTRACT. P ppm	EXCHANGEABLE CATIONS Ca	Mg	K	EXCHANGE ACIDITY KCl(Al)	KCl(TOT)	Ba(Ac)2	TOTAL C.E.C.	BASE SATURATION %
					cmol/kg							
C1	4.0	2.42	0.19	9.0	5.9	0.9	1.1	7.1	7.6	12.8	22.5	35.1
C2	3.9	1.50	0.18	1.0	1.1	0.4	0.8	11.5	12.4	15.6	23.8	9.7
C3	3.9	0.94	0.16	1.0	0.4	0.2	0.6	13.2	14.8	16.7	21.3	5.6
C4	3.6	0.60	0.14	1.0	0.2	0.2	0.5	14.0	15.2	16.8	21.4	4.2
C5	3.4	N.D.	0.13	1.0	0.1	0.1	0.4	14.4	15.7	14.8	18.7	3.2
C6	3.4	N.D.	0.13	1.0	0.0	0.1	0.4	12.4	13.4	14.1	17.3	2.9
C7	3.4	N.D.	0.04	1.0	0.0	0.1	0.3	12.0	13.9	14.8	17.5	2.3
D1	3.9	3.91	0.18	24.0	4.6	1.3	1.5	4.8	5.6	14.8	22.5	32.9
D2	4.0	2.23	0.13	3.0	1.3	0.4	1.0	8.9	9.8	16.1	21.2	12.7
D3	4.0	1.38	0.13	2.0	0.6	0.2	0.8	9.8	10.4	14.6	19.9	8.0
D4	3.7	0.64	0.12	1.0	0.7	0.2	0.6	13.5	15.0	16.0	19.7	7.6
D5	3.4	N.D.	0,11	3.0	0.9	0.2	0.3	12.6	14.4	15.3	17.4	8.0
D6	3.3	N.D.	0.12	1.0	1.3	0.2	0.3	11.9	13.5	15.7	18.1	9.9
D7	3.3	N.D.	0.12	1.0	1.6	0.2	0.3	10.5	12.5	14.4	17.8	11.8

N.D...NOT DETERMINED

microorganisms and elemental solubility. Slightly higher pH values in the surface horizons of all profiles is attributed to leaching of active acidity from the more moist lower slope positions, and to the retention and cycling of plant nutrient cations, particularly Ca and Mg. The higher values observed in profiles C and D may reflect the less acidic nature of lithologically distinct glacial materials in the surface horizons.

There is a continuous drop in pH with increasing depth in these soils. Carson and Dixon (1983) observed a very similar pH distribution for an inland acid sulfate soil in Texas. Declining pH through the profile is unusual for Gray Luvisols developed in other parent materials, however. Howitt and Pawluk (1985) studied an Orthic Gray Luvisol near Breton and found little change in pH with depth in a profile developed in glacial till. For the Boundary soil, lower pH values in the lower solum are attributed to the release of acidity during pyrite oxidation. The solubility and speciation of Al is very sensitive to small pH shifts in the pH range 4.0 to 5.0, and subtoxic levels of Al^{3+} in profiles C and D may be a major factor in improved plant growth in lower slope positions.

5.3.2 ORGANIC CARBON

Total C was determined by dry combustion for surface samples from the four soil profiles. Results of this analysis are presented in Table 9. Since no carbonates are present in any of the profiles, total C can be considered equivalent to organic C. Organic C levels determined for this catena are similar to those found in other Luvisolic soils. Howitt and Pawluk (1985) found organic C levels of 2.3 % in Aeh horizons and 0.4 % for Bt horizons of a Gray Luvisol near Breton.

Organic C content is generally higher in samples from the lower slope positions, reflecting the slower rates of decomposition in cooler, more moist locations. Increased organic C content in lower slope positions may also reflect chemical factors in the soil which encourage plant growth, compared to upper slope positions. The implications of a higher organic matter content for plant growth include the chelation of Al^{3+} and other toxic metal cations, and the provision of a pool of plant nutrients, particularly N and P.

5.3.4 TOTAL NITROGEN

Values obtained for total N are presented in Table 9. Total N levels obtained by Howitt and Pawluk (1985) of 0.03 % to 0.05 % for a Luvisol near Breton are considerably lower than levels obtained in the present study for the Boundary soil. Pawluk (1970) found levels of 0.13 % to 0.31 % for a Fera Eluviated Gleysol developed in acidic parent materials. While total N levels for the soil samples generally increase or decrease with changes in organic carbon, the C/N ratio fluctuates widely through the catena. C/N ratios for the catena vary from 3.7 to 21.7 (calculations not shown) and are lower than for similar soils developed on glacial till. The ratio of C/N is higher in lower slope positions, indicating that the plant community in lower slope positions is more likely to be restricted by the N supply, while other factors may be more important in limiting growth in upper slope positions.

5.3.4 AVAILABLE PHOSPHORUS

Results of extractable P determinations are presented in Table 9. The medium strength Bray modified method extracts all Ca-P, and a portion of Fe-P and Al-P. The following framework for interpretation of test results is given by Olsen and Sommers (1982): less than 3 mg kg^{-1}, very low; 3 to 7 mg kg^{-1}, low; 7 to 20 mg kg^{-1}, medium; greater than 20 mg kg^{-1}, high. Alexander (1968) studied fractionation of P in a Boundary soil profile and in a Luvisolic soil near Breton and obtained extractable P levels similar to those determined in this study. Fe-P and occluded P accounted for 85 to 95% of total inorganic P for Boundary soil, while Ca-P was a much more important source in the profiles from Breton (Alexander, 1968).

Results obtained for this catena indicate very low levels of extractable P for all subsurface horizons. Higher levels of extractable P in surface horizons throughout the catena illustrates the importance of P cycling in these nutrient poor soils. Low values for profiles A, B, and C indicate that deficiencies of P could influence plant growth in these upper and mid slope positions. Dieback of terminal leaders observed in aspen trees in site C may reflect P deficiency in midslope locations. Tree growth in upper slope positions, however is so poor that demands for plant nutrients such as P may not be great enough to induce a deficiency of this element.

Extractable P levels for profile D change dramatically with depth. The exploitation of surface horizons for P appears necessary for adequate P nutrition of plants in these soils.

5.3.5 CATION EXCHANGE

Results of analyses for exchangeable cations, exchange acidity, and total C.E.C. are presented in Table 9. These data emphasize the very low base saturation of the soils of the catena. Ca is the dominant nutrient cation in the surface horizons of all profiles and in the entire D profile. K, rather than Ca predominates in the lower portions of profiles A, B and C. The decline in exchangeable nutrient cations with depth in the upper and mid slope profiles is attributed to the extremely acidic nature of the shale parent material and to the absence of a mineral source for Ca ($CaCO_3$). Total cation exchange capacity of soil samples is slightly higher for surface horizons, reflecting higher organic matter content, pH and clay content of these samples.

The cause of the increase in exchangeable Ca with depth in site D may be related to solute interflow in pore waters, or interactions with groundwater.

Exchange acidity measured in $BaAc_2$ was relatively constant with depth and accounted for 55 % (sample C1) to 88 % (sample D5) of the total C.E.C. Exchange acidity measured with KCl was lower than $BaAc_2$ acidity, indicating the difference between buffered ($BaAc_2$) and unbuffered (KCl) extraction. Complexation of Al with KF and subsequent titration of extracts revealed that Al hydrolysis accounted for a major portion of KCl acidity.

Extraction of samples from profiles A and D with NH_4OAc buffered at pH 4.8 enabled the measurement of exchangeable Al. Data are presented in Figure 11 illustrating the overwhelming presence of Al on the cation exchange complex of the Boundary soil. According to the Gapon equation, this relationship will also describe the relative solution concentrations of the various ions. Of particular interest is the ratio of Al to (Ca+Mg). Ulrich (1984) states that the Al/(Ca+Mg) ratio provides a reliable measurement of the status of soil environments affected by acid rain. A ratio greater than 1 indicates that serious ecosystem degradation is occurring. For the catena under investigation in this study, sample D1 is the only sample where the Al/(Ca+Mg) ratio exceeds 1.

For a Luvisolic soil developed in glacial till, (Howitt and Pawluk, 1985) approximately 70 % to 80 % of the total cation exchange capacity was accounted for by Ca. Pawluk and Dudas (1981) found exchangeable acidity to be less than 40 % of total cation exchange capacity for all horizons of a Luvisolic soil developed in eolian sand. The data from the Boundary soil, which is a natural system unaffected by aerial contamination emphasize the severity of the soil environment associated with acid sulfate soils. The hardiness of plant species which pioneer on such sites, and their ability to extract sufficient nutrients from these depleted soil solutions is a matter of considerable interest.

5.3.6 EXTRACTABLE IRON AND ALUMINUM

Table 10 shows the amounts of Fe and Al extracted with dithionite-citrate-bicarbonate (D-C-B), oxalate, and pyrophosphate. Patterns of Fe accumulation and translocation vary across the catena.

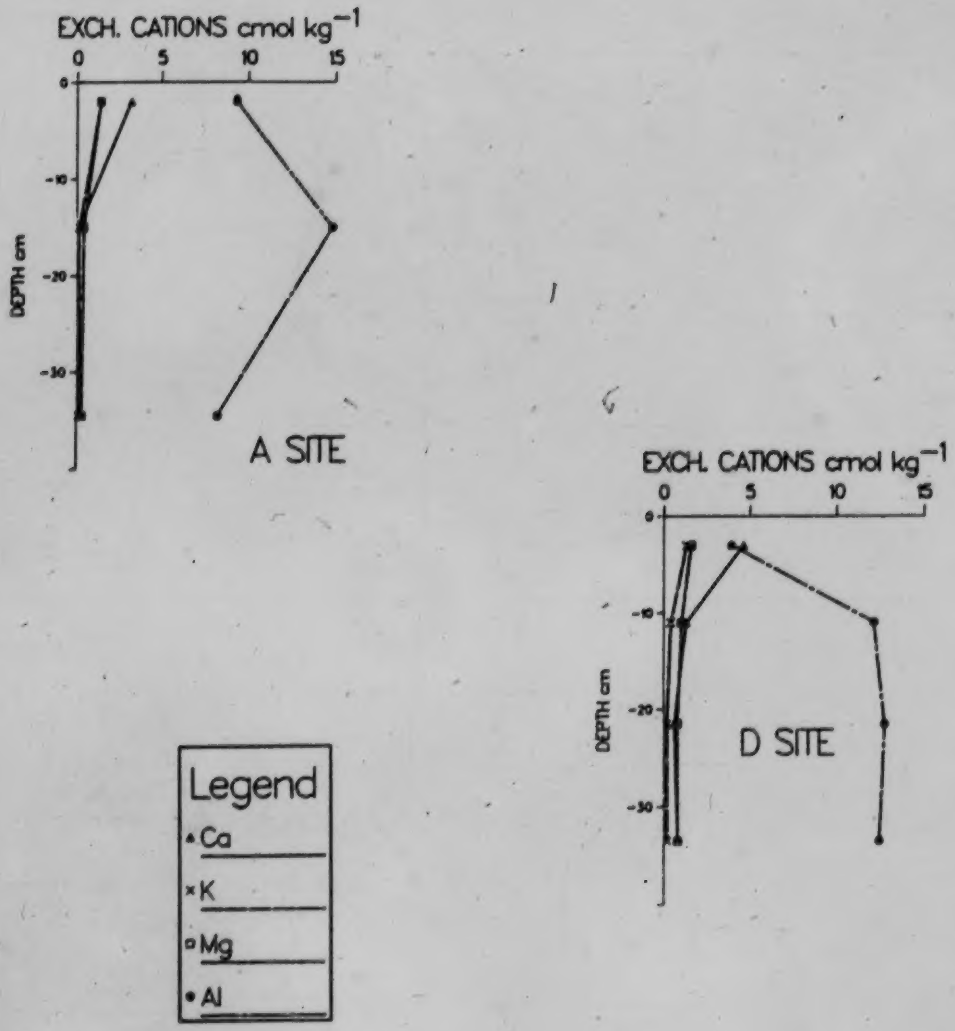

FIGURE 11. Exchangeable cations (NH_4OAc pH 4) for upper solum of profiles A and D. The dominance of Al on the exchange complex of all samples except D1 reflects the very low base saturation of these soils.

TABLE 10. Extractable iron and aluminum levels for catena soils.

	DITHIONITE EXTRACTABLE		OXALATE EXTRACTABLE		PYROPHOSPHATE EXTRACTABLE	
	%IRON	%ALUMINUM	%IRON	%ALUMINUM	%IRON	%ALUMINUM
A1	3.90	0.39	0.60	0.29	0.51	0.31
A2	4.67	0.38	0.86	0.30	0.81	0.37
A3	6.92	0.20	1.62	0.17	0.21	0.21
A4	3.26	0.18	0.41	0.14	0.17	0.14
A5	4.00	0.18	0.23	0.14	0.10	0.12
A6	3.82	0.16	0.19	0.13	0.10	0.07
A7	5.66	0.16	0.28	0.12	0.08	0.04
B1	3.18	0.25	0.66	0.25	0.40	0.29
B2	4.02	0.36	0.91	0.28	0.68	0.35
B3	4.17	0.25	0.93	0.22	0.65	0.31
B4	3.32	0.19	0.37	0.19	0.18	2.23
B5	4.32	0.17	0.22	0.16	0.10	0.16
B6	4.18	0.15	0.21	0.17	0.09	0.12
B7	3.97	0.19	0.37	0.17	0.10	0.17
C1	2.59	0.21	0.77	0.24	0.38	0.26
C2	3.38	0.40	0.76	0.42	0.48	0.39
C3	3.57	0.37	0.74	0.35	0.60	0.36
C4	3.76	0.31	1.20	0.27	0.62	0.30
C5	3.24	0.26	0.56	0.21	0.22	0.25
C6	2.87	0.17	0.31	0.17	0.13	0.19
C7	3.29	0.17	0.30	0.17	0.10	0.15
D1	1.56	0.19	0.57	0.21	0.22	0.17
D2	2.21	0.37	0.93	0.41	0.44	0.36
D3	2.81	0.51	1.07	0.56	0.35	0.43
D4	3.06	0.27	0.78	0.29	0.26	0.31
D5	3.47	0.19	0.51	0.19	0.26	0.27
D6	3.98	0.17	0.52	0.17	0.25	0.20
D7	4.42	0.13	0.57	0.13	0.26	0.16

Levels of D-C-B extractable Fe for profile A are greater than values obtained by other authors for Boundary soil (Pawluk and Dudas, 1978; Clark and Green, 1963) and other inland acid sulfate soils (Carson and Dixon, 1983; Mermut et al., 1985). D-C-B extractable Fe levels for profile D compare more closely with results from these previous studies. Horizons of accumulation of crystalline forms of Fe often coincide with horizons of clay accumulation, but there are several exceptions, especially in profiles A and B. Different processes are involved in translocation of Fe, Al and clay.

The distribution of amorphous Fe oxides (oxalate - pyrophosphate) shows no common trend over the catena. The large accumulation of amorphous forms observed in sample A3 give an indication of the unique character of profile A.

Pyrophosphate Fe has accumulated in the B horizons of all the soil profiles, but the high clay content of these soils excludes them from classification as Bf horizons (pyrophosphate [Al+Fe]/clay % <0.05). Translocation of Fe and Al is evident, therefore these horizons may be designated as Btfj.

High levels of D-C-B extractable Fe in BC and C horizons of profiles A and D are attributed to the presence of natrojarosite and suggest that natrojarosite is more stable in the lower solum than near the surface. This is indicated by sharper jarosite reflections in X-ray patterns as well. The large difference in D-C-B extractable Fe between samples A3 and A4 indicates the most dramatic property of this profile when viewed in the field. The deep reddish color of the A3 horizon, and the drab gray color of the A4 with the sharp horizon boundary between them reflects a major change in the pedo-environment across a depth range of only 10 cm. This marks the upward extent of visible concentrations of natrojarosite in the profile, and the lower limit of extensive root development and plant water extraction. D-C-B extractable Fe levels in sample A7 are similar to those in sample A3, but goethite and possibly hematite are the dominant forms of Fe in sample A3, while natrojarosite is a dominant Fe containing mineral in sample A7.

There is a decrease in D-C-B extractable Fe in lower slope positions. This is associated with lower clay content in profile D and may be partially attributed to the mixing of glacial materials with the shale parent material. Lower levels of D-C-B extractable Fe in profiles B and C may reflect periodic leaching of Fe from these profiles.

The distribution of Fe in the catena may have implications regarding plant growth response. The association of plant nutrients and toxic cations with Fe oxides is well documented. For these reasons, the very high levels of D-C-B and oxalate extractable Fe in samples such as A3 might be expected to affect other soil chemical properties such as extractable P and cation exchange characteristics. This does not appear to be the case, however as no consistent relationship is observed between extractable Fe and these other soil chemical properties. There is, however a relationship observed between root proliferation in the soil profiles and the presence of visible natrojarosite. Few roots penetrate the horizons where natrojarosite is observed.

5.3.7 TOTAL ELEMENTAL ANALYSIS

Elemental composition of the Boundary soil parent materials (average values for samples A7, B7, C7 and D7), natrojarosite, and veinlet iron oxides are presented in comparison with average values for the earth's crust and for shales (Brownlow, 1979; Kabata-Pendias and Pendias, 1984; Bowen, 1979) in Table 11. A sample of standard reference material SO-1 (Bowman et al., 1979) was included for I.N.A.A. to provide a check of analytical accuracy and the results are also presented in Table 11. SO-1 is a soil material prepared by the Canadian Certified Reference Materials Project and is a weathered marine sediment with a clay content of 80 %. Values obtained by I.N.A.A. for SO-1 in the present study are similar to those obtained by Warren and Dudas (1986). I.N.A.A. slightly underestimated the levels of the major elements Al, Fe, Ca, Mg and Ti. For the trace elements V, Nd, Sm, As and Eu, the analysed levels were more than 2 standard deviation units below reported values, while Zn and U levels were higher than the reported values.

TABLE 11. Average elemental composition of the earth's crust and shales, compared with determined values for soil materials from catena (P.G.M., natrojarosite, and veinlet Fe oxides) and standard reference material SO-1.

	CRUST	SHALE	P.G.M.	NATROJAROSITE	VEINLET	SO-1
Al (%)	8.2	8	8	0.67	3.56	7.4
Fe "	5.6	4.7	4.8	29	23	5.47
Ca	4.1	2.5	<0.2	<0.2	<0.2	1.3
Na	2.4	0.7	0.4	2.9	0.5	1.7
Mg	2.3	1.3	0.43	<0.05	0.2	1.7
Ti (mg/kg)	5700	4500	4075	300	1800	3700
Mn "	950	850	23.8	4.7	12	760
Ba	425	580	1030	240	370	850
V	135	130	240	44	690	98
Cr	100	100	110	91	100	160
Rb	90	140	160	70	80	130
Zn	70	80	107	<15.0	44	170
Ce	67	50	71	87	34	99
Nd	28	23	24	27	12	40
La	25	40	41.2	33.3	19.2	52.3
Co	25	20	3.5	0.8	1.8	25
Sc	22	10	16.5	5.1	11.5	17.7
B	10	100	138	15	77	20
Th	9.6	11	11.5	9.7	7.4	10
Sm	7.3	6.5	4.3	2.27	2.67	6.92
Dy	5.8	4.5	2.8	0.3	1.5	3.2
Hf	3	6	4	0.3	1.9	2.2
Cs	3	5	9.8	0.9	3.9	4.9
U	2.7	3.2	5.2	0.6	3.3	1.7
Br	2.5	6	0.7	<0.5	3.5	1.3
As	1.8	6.6	36.5	61	400	1
Mo	1.5	2	6.3	9	11	<2.0
W	1.5	2	1.3	1	<1.0	1
Ta	1.5		0.9	<0.5	0.5	<0.5
Eu	1.2	1	0.8	0.43	0.52	1.42
Yb	1.2		2.3	0.21	1.16	2.16
Tb	1.1	0.9	0.4	<0.3	0.4	0.8
Lu	0.8	0.7	0.4	0.04	0.21	0.31
Sb	0.2	1.5	1.4	0.4	2.1	0.1
Se	0.1	0.6	1.4	2.7	3	<0.8

Analysed values for Ag, Au, Ca, Cl, I and In were below detection limits for the parent materials. Levels reported for Ni, Se, Sr, and W are very close to detection limits of the analysis.

The parent material of the Boundary soil has low concentrations of Br, Ca, Co and Mn compared to average values for shales. These elements may be lost from the sediment in the reduction stage during pyrite formation or they may be mobilized and leached in the strongly acid environment of the oxidation stage of acid sulfate soil genesis.

The Ca content of the Boundary soil parent materials is lower than any value reported in McKeague and Desjardins (1979) for Canadian soils. Spiers (1982) obtained an average Ca content of 1.24 % for parent materials in northeastern Alberta. Total Ca for acid sulfate soils in other areas of the world are similar to the levels obtained for the Boundary soil in the present study. For three acid sulfate soils in Thailand, Maneewon et al. (1984) reported total Ca levels of 0.11, 0.25 and 0.26 %.

Co levels reported by Pawluk and Dudas (1981) for glacial till parent materials of a Gray Luvisol near Cooking Lake are 10 to 12 mg kg^{-1}. Spiers (1982) found an average Co content of 18 mg kg^{-1} for parent materials in northeastern Alberta. As shown in table 11, the Co content of Boundary soil parent materials (3.5 mg kg^{-1}) are much lower than these reported values.

The range of Mn content for Canadian soils reported by McKeague and Desjardins (1979) is 100 to 1200 mg kg^{-1}. Spiers (1982) reported 254 mg kg^{-1} as an average for northeastern Alberta. The extremely low levels of Mn in the Boundary soil parent materials are not typical of acid sulfate soils in Thailand. Maneewon et al. (1984) found total Mn of 178, 113 and 525 mg kg^{-1} for three profiles.

The parent materials are enriched in B, Ba, As and V relative to the average for shales. Enrichment of a particular element indicates incorporation into pyrite or other minerals during the reduction stage and subsequent retention by adsorption or precipitation during pyrite weathering and soil development. There are few reports of the total B content of Alberta soils. Values reported in Table 11 are high relative to the average for shales. Bradford (1966) states that marine sediments are high in B because of the relatively high B content of seawater (5 mg kg^{-1}) and suggests that micaceous minerals concentrate B.

Dudas and Pawluk (1981) found As levels of approximately 6 mg kg^{-1} for a Luvisolic soil near Cooking Lake. Dudas (1984) reported enrichment of As in the Boundary soil and attributed the high levels for this soil to the scavenging of As by secondary Fe oxides. Pyrite is believed to be the source of the As.

Total elemental analysis provides an initial estimation of nutritional and toxic factors impinging on plant growth in soil environments. Low levels of Ca and Mg suggest that these required plant nutrients may be limiting factors in the catena. High levels of As, B, Ba, and V may implicate these elements in toxic effects. Other nutrient elements which differ considerably from values in the literature are Zn and Mo. Zn levels of 52 mg kg^{-1} were reported by Dudas and Pawluk (1981) for a Gray Luvisol developed in till, while Spiers (1982) reported an average of 58 mg kg^{-1} Zn for parent materials from northeastern Alberta. Levels for the Boundary soil (Table 11) are somewhat higher than these values, although the differences may be partially caused by analytical error in the I.N.A.A., since Zn levels for SO-1 are also elevated relative to the accepted value. Mo levels of 1.9 mg kg^{-1} reported by Spiers are considerably lower than those determined in the present study. Immobilization of Mo by fixation in the strongly acid Boundary soil may result in accumulation of this element.

Changes in elemental concentration within profiles and across the catenary sequence reflect redistribution in the weathering environment. Redistribution occurs as a result of a number of chemical processes including dissolution-precipitation, oxidation-reduction, and adsorption-desorption. Physical processes such as lessivage and biological immobilization also affect the distribution of chemical constituents in soils. Factors controlling elemental distribution in the catena impact upon the solution concentration of the elements, and therefore plant availability.

Major patterns of elemental distribution observed in the catena are presented in Figures 12, 13 and 14. Figure 12 depicts the accumulation of Br, Cs and Fe in B horizons of profile C. This distribution pattern was commonly observed in profiles A, B and C. Other elements showing similar trends are Al, As, Nd, Th and V. Most of the elements that accumulate in B horizons are associated with clay particles and are transported with illuvial clay. Adsorption to mineral surfaces restricts the availability of As, Th and V in acidic soils, which may prevent toxic effects of these elements. Soil profile D does not possess a strong illuvial horizon, and the trend illustrated in Figure 12 is not observed in the lower slope position.

Figure 13 shows concentration profiles for Sc, Sm and U for the C pit. These elements are depleted from surface horizons. This pattern is also observed for Ce, Eu, La, Lu and Na in profiles A, B and C. Elements displaying this pattern of distribution have been dissolved from crystals and released into the soil solution in highly weathered surface horizons. These elements may be present in high concentrations in the soil solution and are easily available to plants.

Figure 14 illustrates changes in Mn concentration in profiles A and C. Enrichment in surface horizons is also observed for Co, Hf and Ti. Mn accumulates in surface horizons as a result of complexation with organic matter, which prevents leaching losses. Biological cycling of Mn may be extremely important in supplying this required plant nutrient. Low total levels of Mn may indicate deficiency of this element in locations where organic reserves are not present or are not mineralized rapidly. Hf and Ti are negatively enriched in surface horizons due to the stability of the minerals in which they occur.

Further information regarding the behavior of the elements analysed for by I.N.A.A. may be derived from studying the correlation between the elemental concentrations for all the soil samples. Table 12 presents such a correlation matrix. The elements which are highly correlated with Al (As, B, Ce, Cr, Cs, La, Mg, Mo, Nd, Sb, Th, V) are probably associated with clay minerals, either through incorporation

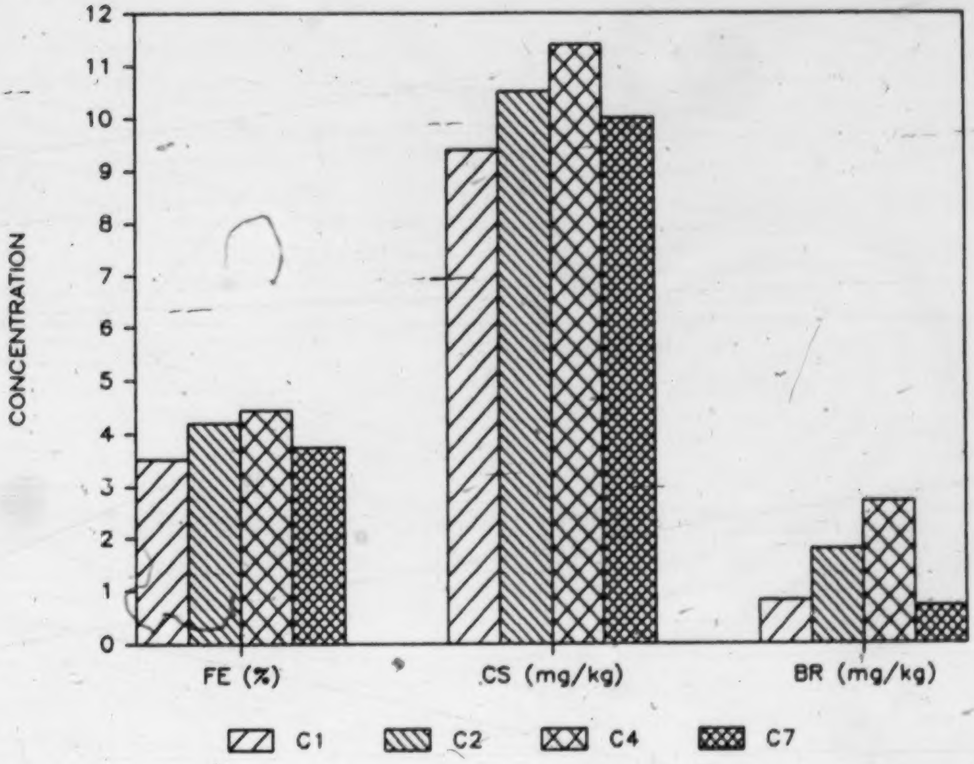

FIGURE 12. Profile distribution of Fe, Cs and Br in site C. Accumulation in the B horizon is a commonly observed pattern in the Boundary soil.

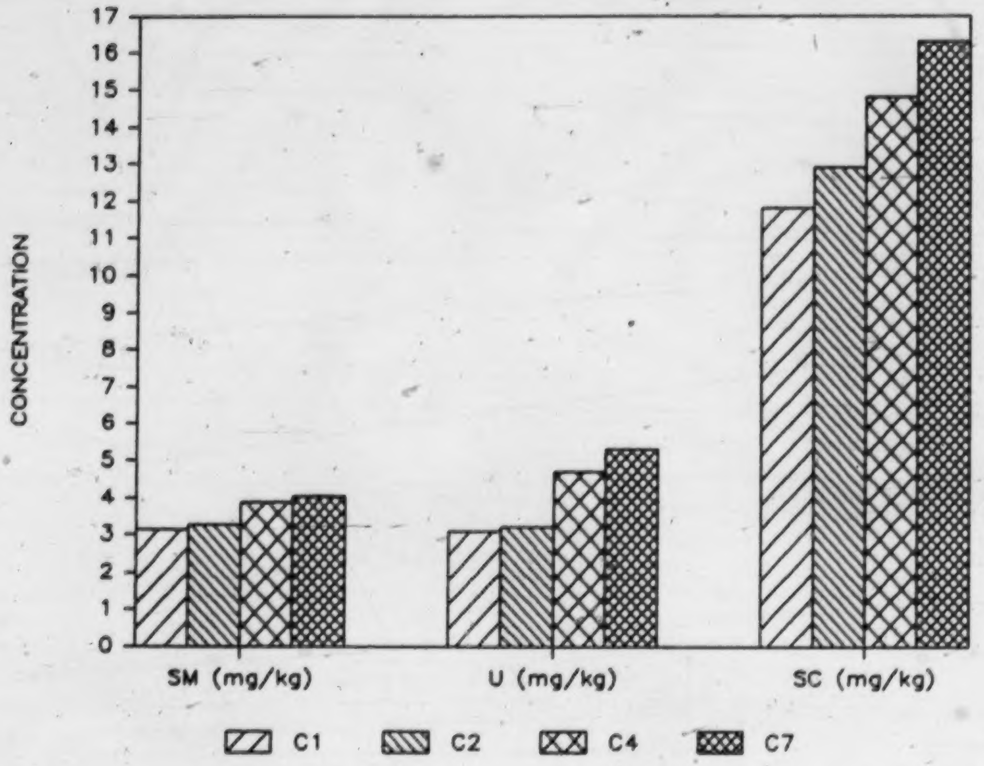

FIGURE 13. Profile distribution of Sm, U and Sc in site C. Higher elemental concentration in the lower solum is attributed to depletion from surface horizons resulting from mobilization and leaching.

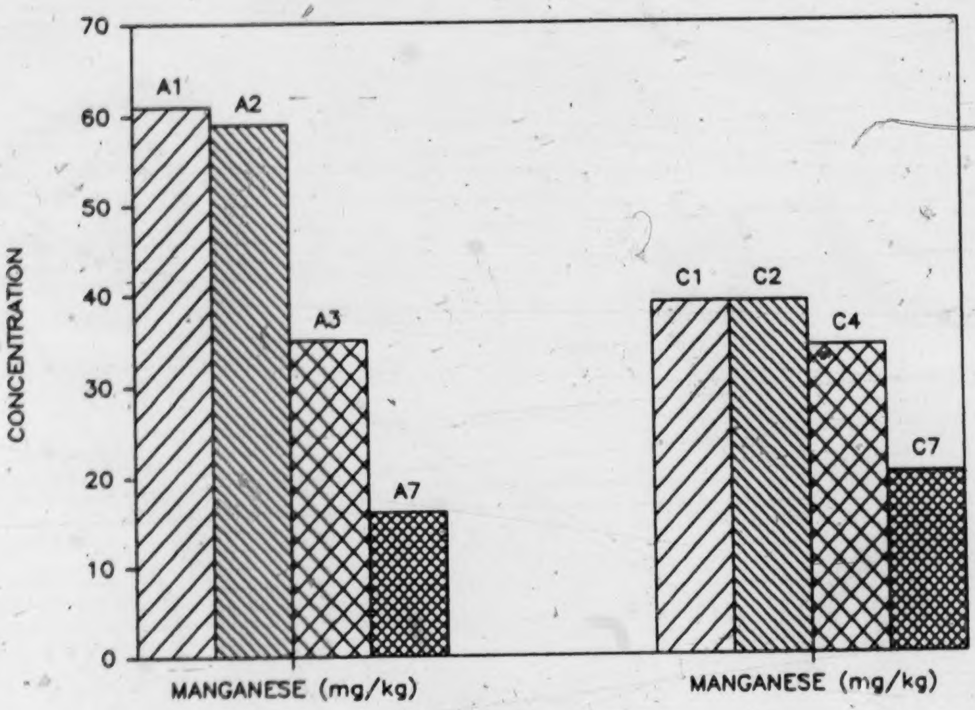

FIGURE 14. Profile distribution of Mn in sites A and C, illustrating accumulation in the upper solum, attributed to complexation of Mn with organic matter.

TABLE 12. Correlation matrix of chemical constituents for soil samples from all profiles.

	Al	As	B	Ba	Br	Ce	Co	Cr	Cs	Dy	Eu	Fe	Hf	La	Lu	Mg
As	0.771*	1.000														
B	0.763*	0.760*	1.000													
Ba	0.477	0.435	0.527	1.000												
Br	0.309	-0.095	-0.034	-0.231	1.000											
Ce	0.781*	0.756*	0.862*	0.482	-0.073	1.000										
Co	-0.524	-0.377	-0.464	-0.449	-0.038	-0.499	1.000									
Cr	0.950*	0.777*	0.821*	0.424	0.208	0.867*	-0.433	1.000								
Cs	0.963*	0.749*	0.794*	0.483	0.363	0.752*	-0.614	0.919*	1.000							
Dy	0.234	0.113	0.118	-0.098	0.116	0.186	0.258	0.319	0.174	1.000						
Eu	0.291	0.386	0.498	0.323	-0.403	0.770*	-0.192	0.431	0.205	0.065	1.000					
Fe	0.406	0.705*	0.625*	0.559	-0.221	0.510	-0.102	0.486	0.412	0.111	0.306	1.000				
Hf	-0.649*	-0.678*	-0.647*	-0.524	0.216	-0.656*	0.712*	-0.600	-0.630*	0.140	-0.334	-0.359	1.000			
La	0.873*	0.817*	0.895*	0.520	0.010	0.981*	-0.538	0.919*	0.843*	0.155	0.663*	0.530	-0.700*	1.000		
Lu	0.068	0.019	0.342	0.089	-0.186	0.574	-0.011	0.296	0.042	0.201	0.800*	0.080	-0.086	0.427	1.000	
Mg	0.899*	0.687*	0.583	0.229	0.267	0.727*	-0.281	0.897*	0.780*	0.313	0.384	0.262	-0.532	0.787*	0.202	1.000
Mn	-0.535	-0.608	-0.765*	-0.559	0.320	-0.777*	0.804*	-0.577	-0.608	0.132	-0.553	-0.454	0.774*	-0.758*	-0.341	-0.323
Mo	0.815*	0.771*	0.861*	0.575	0.072	0.815*	-0.583	0.818*	0.823*	0.052	0.392	0.632*	-0.713*	0.867*	0.176	0.625*
Na	-0.303	0.066	0.081	-0.136	-0.544	0.238	-0.176	-0.165	-0.268	-0.084	0.400	0.072	-0.271	0.106	0.489	-0.270
Nd	0.717*	0.636*	0.825*	0.474	0.026	0.870*	-0.434	0.769*	0.701*	-0.019	0.718*	0.496	-0.466	0.875*	0.476	0.642*
Rb	0.280	0.131	-0.225	-0.109	0.459	-0.173	-0.380	0.055	0.265	-0.234	-0.465	-0.315	-0.282	-0.050	-0.604	0.283
Sb	0.863*	0.848*	0.864*	0.419	0.100	0.791*	-0.383	0.935*	0.877*	0.302	0.318	0.623*	-0.612	0.847*	0.202	0.771*
Sc	0.581	0.652*	0.860*	0.542	-0.264	0.887*	-0.318	0.740*	0.569	0.276	0.709*	0.686*	-0.575	0.843*	0.637*	0.500
Sm	0.409	0.417	0.622	0.321	-0.276	0.836*	-0.147	0.561	0.334	0.190	0.950*	0.292	-0.305	0.745*	0.831*	0.483
Ta	-0.112	-0.030	0.330	0.000	-0.253	0.035	0.355	0.000	-0.109	0.198	0.102	0.138	0.078	0.018	0.229	-0.138
Tb	0.294	0.252	0.381	0.207	-0.097	0.518	-0.060	0.491	0.297	-0.036	0.553	0.237	-0.030	0.483	0.564	0.338
Th	0.816*	0.776*	0.840*	0.375	0.203	0.845*	-0.403	0.884*	0.814*	0.422	0.429	0.656*	-0.517	0.873*	0.326	0.714*
Ti	-0.297	-0.587	-0.351	-0.119	0.389	-0.540	0.287	-0.395	-0.274	0.035	-0.465	-0.400	0.602	-0.504	-0.241	-0.311
U	0.348	0.358	0.669*	0.198	-0.245	0.785*	-0.289	0.526	0.323	0.307	0.799*	0.314	-0.301	0.695*	0.813*	0.358
V	0.959*	0.830*	0.819*	0.587	0.246	0.772*	-0.498	0.932*	0.962*	0.230	0.258	0.576	-0.637*	0.860*	0.060	0.807*
Yb	-0.089	-0.126	0.143	0.007	-0.264	0.350	0.208	0.142	-0.129	0.117	0.680*	-0.102	0.092	0.213	0.914*	0.121
Zn	-0.569	-0.630*	-0.719*	-0.461	0.001	-0.597	0.774*	-0.560	-0.669*	0.044	-0.177	-0.557	0.641*	-0.641*	-0.027	-0.310

TABLE 12 cont. Correlation matrix of chemical constituents for soil samples from all profiles.

	Mn	Mo	Na	Nd	Rb	Sb	Sc	Sm	Ta	Tb	Th	Ti	U	V	Yb
As															
B															
Ba															
Br															
Ce															
Co															
Cr															
Cs															
Dy															
Eu															
Fe															
Hf															
La															
Lu															
Mg															
Mn	1.000														
Mo	-0.750*	1.000													
Na	-0.416	-0.016	1.000												
Nd	-0.650*	0.670*	0.025	1.000											
Rb	0.121	-0.017	-0.307	-0.186	1.000										
Sb	-0.610	0.832*	-0.113	0.674*	-0.013	1.000									
Sc	-0.739	0.777*	0.326	0.719*	-0.480	0.764*	1.000								
Sm	-0.535	0.466	0.355	0.764*	-0.507	0.446	0.782*	1.000							
Ta	-0.009	0.127	0.037	0.026	-0.640*	0.164	0.316	0.219	1.000						
Tb	-0.278	0.237	0.066	0.503	-0.371	0.392	0.492	0.610	0.037	1.000					
Th	-0.595	0.840*	0.030	0.709*	-0.069	0.882*	0.812*	0.544	0.071	0.329	1.000				
Ti	0.525	-0.390	-0.607	-0.315	0.030	-0.393	-0.500	-0.370	0.184	-0.340	-0.351	1.000			
U	-0.623*	0.506	0.549	0.636*	-0.502	0.472	0.836*	0.855*	0.322	0.479	0.655*	-0.391	1.000		
V	-0.503	0.845*	-0.288	0.709*	0.103	0.923*	0.653*	0.380	-0.054	0.285	0.855*	-0.272	0.331	1.000	
Yb	-0.100	-0.089	0.327	0.325	-0.509	0.068	0.415	0.715*	0.288	0.622*	0.045	-0.100	0.584	-0.097	1.000
Zn	0.815*	-0.780*	-0.165	-0.502	-0.112	-0.657*	-0.509	-0.205	0.049	-0.061	-0.721*	0.250	-0.436	-0.664*	0.254

* denotes significance at 99% level

into the crystal by isomorphous substitution (Cs and Mg) or through adsorption onto the surface of the particles (As, Mo, Sb, Th and V). Elements which are highly correlated with Al also tend to be correlated with each other. Correlation coefficients for Fe are lower than expected, given the affinity of many elements for Fe oxides. Low correlation coefficients for Fe are attributed to the different forms of Fe present in surface horizons compared to the parent materials. Much of the Fe in the parent materials is present as natrojarosite. Total Fe content of soil samples from the lower solum does not reflect the surface properties which are responsible for the reactive nature of Fe oxides.

Positive correlations between Co, Mn, Hf and Zn are apparent from the data presented in Table 12. In general, these elements are negatively correlated with Al and Fe. McKeague and Desjardins (1979) observed high positive correlations between Fe and Co for certain soils and suggested that such correlations are related to a close association between these elements in silicate structures. Dudas and Pawluk (1980) suggest that the ability of Zn to substitute for Fe in Fe^{++} positions in crystals accounts for a close association between these two elements. In the Boundary soil, however, secondary forms of Fe predominate and these positive correlations are not observed.

Comparison of averaged concentrations for the surface samples from sites A and D provides a measure of elemental availability which may help explain the dramatic differences in growth response observed between the two locations. Table 13 compares the averaged values of samples A1, A2 and A3 with average elemental composition of D1, D2 and D4. Many elements with potentially toxic effects, such as As, B, Sb, Th and V are more concentrated in the A site. Mn is more concentrated in the lower slope position. Ca levels are too low to establish a trend. Total elemental analysis provides information useful in investigating potential toxicity or deficiency effects. Further information on elements of interest can be achieved through solution extractions or by direct analysis of plant tissues.

TABLE 13. Elemental composition of surface samples from upper (A) and lower (D) slope positions.

	PROFILE A	PROFILE D		PROFILE A	PROFILE D
Al (%)	8.4	7.9	B (mg/kg)	130.0	99.3
Fe "	6.3	2.9	Th "	12.3	8.2
Ca	--	--	Sm	3.4	3.4
Na	1367	2133	Dy	3.6	2.6
Mg	0.46	0.39	Hf	4.3	4.9
Ti (mg/kg)	4267	4433	Cs	10.1	8.1
Mn "	51.7	73	U	4.0	3.7
Ba	1050	840	Br	1.4	1.8
V	263	190	As	40	21
Cr	113.0	93.3	Mo	6.3	3.3
Rb	167	167	W	1.0	1.3
Zn	113	173	Ta	0.9	0.8
Ce	65	56	Eu	0.57	0.58
Nd	22.7	20.3	Yb	2.01	2.20
La	39.1	32.6	Tb	0.37	0.37
Co	4.6	5.0	Lu	0.35	0.37
Sc	15.0	11.2	Sb	1.6	0.8

5.4 VEGETATION

5.4.1 PLANT GROWTH RESPONSE

Height and diameter measurements for aspen trees from upper (A), mid (BC) and lower (D) slope positions are presented in Figure 15. Tree ring counts for one sample tree from each location indicated ages of 41, 39 and 41 years respectively. Annual growth was fairly consistent since establishment for all sites, with the exception of very poor growth years associated with unfavourable climatic conditions around age 20 years. The observation of very narrow growth rings at specific locations in stems from various sites may indicate drought or insect defoliation which severely limits growth of all trees for a short span of time. Consistently poor growth, as observed for site A is probably caused by edaphic factors, since these factors do not exhibit major changes from year to year in natural systems. Considering the many factors which can influence growth response, normal tree growth rates for a particular region are difficult to define. Strong and La Roi (1983) observed height growth of 15.6 m for a 45 year old trembling aspen with a 13 cm diameter stump, and 7.6 m for a 19 year old trembling aspen with a 7 cm stump diameter. Results presented in Figure 15 indicate that growth rates for aspen in site D compare closely with these published values. Growth response of aspen trees in site D is therefore considered to be a typical growth rate for northern Alberta.

A deformed growth habit of aspen poplar was observed in upper slope positions. Dead and dying trees in this location often have stem lesions, twisted stems and dead tops. Some trees have regrowth starting from the base of dead stems. Leaves of such regrowth were often observed to be a very dark green color.

Repeated dieback of tops leads to the sort of stem deformation observed in upper slope positions. Stem lesions are associated with infection by fungal pathogens of the genus Hypoxylon. Sucoff (1982) describes the interaction between the spread of stem cankers

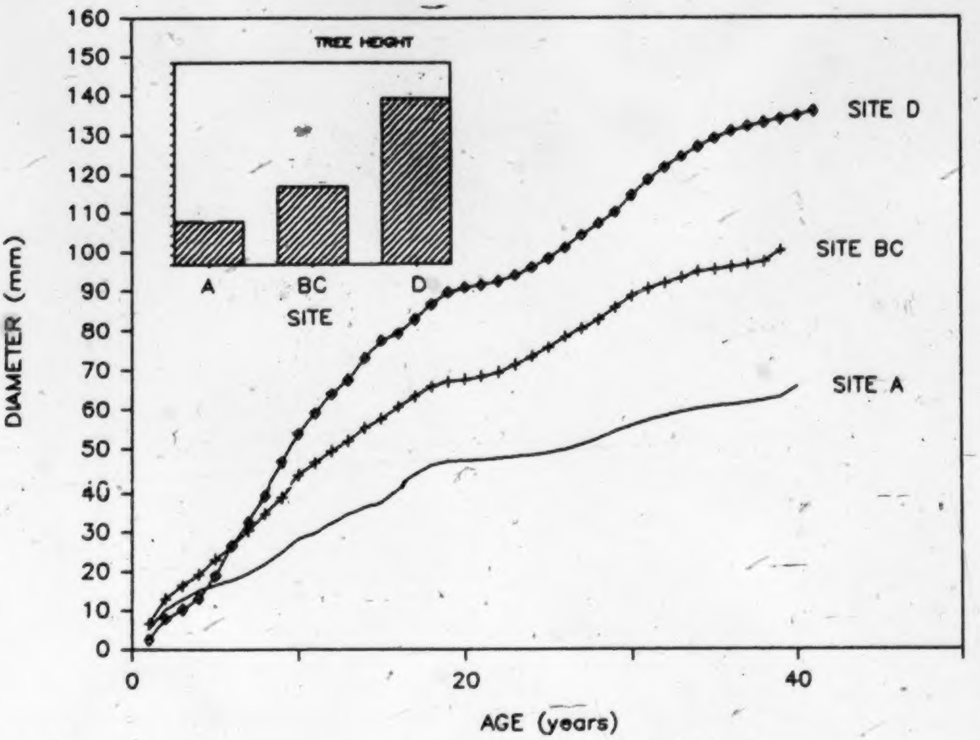

FIGURE 15. Aspen growth response in the catena. Cumulative diameter growth reflects several years of slow growth at ages 19 to 22 as a result of climatic influence or defoliation by insects. Consistently better growth in lower slope positions compared with upper slope positions is attributed to edaphic factors.

and tree moisture status. Infection of aspen by Hypoxylon pruinosum is promoted by tree moisture stress, low humidity and low soil moisture. The reasons for this response, are not known but Sucoff (1982) suggests that mycotoxins may be involved. Dieback may be a symptom of several nutrient disorders such as deficiencies of P, Ca and B while dark green leaves are commonly associated with P deficiency.

Trees in midslope positions appear much healthier than those in upper slope positions and growth response is much better as illustrated by the data shown in Figure 15. Trees in this location still suffer partial dieback in the upper crown, although the form of these trees is not distorted as in site A. The factor causing dieback in site BC may be the same as in site A, with less severe consequences for tree growth. Conversely, the limiting factor in site BC may be different than that in site A, and associated with the greater nutrient requirements of the more productive forest in this location.

5.4.2 PLANT COMMUNITY DESCRIPTION

A summary of the composition of herbaceous species occupying the site is presented in Table 14. The extent of ground cover by herbs corresponds closely with the areas of unrestricted tree growth in lower slope positions. Locations devoid of herbaceous ground cover tend to exhibit poor tree growth as well. Coverage by mosses and lichens, and by leaf litter achieve maximum values in mid slope positions. Most of the ground surface in lower slope positions is covered by litter but the counting method used gave precedence to herbaceous species. A similar situation occurs for mosses and lichens. Reduction of ground cover attributed to leaf litter in upper slope positions is related to poor tree growth in this location. Trees growing in upper slope positions do not produce enough leaves to develop a continuous litter layer. The reduction in ground cover by mosses and lichens in upper slope positions reflects a paucity of litter and deadfall which serve as substrate for these organisms.

Analysis of ground cover is useful for evaluation of forest sites. Vaccinium vitis-ideae is indicative of poor sites for aspen (Schreiner, 1959). The presence of bare ground in upper slope

TABLE 14. Plant community composition determined for vegetation transects V1 (lower slope position) through V8 (upper slope position).

	ALL HERBS	MOSS & LICHEN	LITTER	BARE GROUND	DOMINANT SPECIES (minor species)
	% COVER				
V1	43	1	55	0	Aralia nudicaulis, Linnae borealis, Maeantemum canadensis, Rubus ideais. (Aster conspicuous, Cornus canadensis, Pyrola secunda, Lathyrus ochroleucus)
V2	36	2	62	0	Aralia nudicaulis, Linnae borealis, Epilobium angustifolium, Cornus canadensis. (Lathyrus ochroleucus, Pyrola secunda, Pyrola asarifolia, Maeanthemum canadensis)
V3	11	4	85	0	Linnae borealis, Aralia nudicaulis. (Lathyrus ochroleucus)
V4	15	10	75	0	Linnae borealis, Commandra pallida, Aralia nudicaulis. (Maeanthemum canadensis, Lathyrus ochroleucus)
V5	0	21	79	0	(Prunus pennsylvanica)
V6	0	37	57	6	(Prunus pennsylvanica)
V7	4	16	43	37	Pyrola secunda
V8	0	20	40	43	(Pyrola secunda, Vaccinium vitis-ideae)

positions is stark evidence of the severity of growing conditions since the diversity of species usually allows for the survival of some species on the most austere of sites.

5.4.3 PLANT TISSUE ANALYSIS

Plant tissue analysis provides a direct measure of the nutrient status of a plant, provided that factors which influence elemental concentration are considered. The interpretation of tissue analysis data is discussed by Mengel and Kirkby (1979), Mead (1984), and Ballard and Carter (1986). A critical level of a particular nutrient describes the tissue concentration below which a fertilizer response is expected. Figure 16, after Mengel and Kirkby (1978), illustrates the relationship between nutrient concentration and growth response. The shape of the curve describing the relationship is highly variable, depending on the particular nutrient, plant species and growing conditions being considered. This variability confounds the establishment of critical levels. In addition, the toxic range of an element is a variable function of the plant's ability to sequester excess quantities of harmful ions, or otherwise inactivate them in the tissue. While definitive critical nutrient levels are not established for many species, determinations of a range of acceptable levels may be based on tissue analysis of plants grown under deficient, normal, and toxic conditions.

Elemental concentrations of aspen tree samples from upper, mid and lower slope positions are presented in Table 15. Values obtained by Johnston and Bartos (1977) and by Timmer (1985) are presented for comparison. The analysed sample trees showed dramatically different growth responses (see section 5.4.1). Tree growth response in upper slope positions was poorest, midslope positions were intermediate, and lower slope positions exhibited the best growth. A common limiting factor responsible for the observed growth differences in all sites should show a consistent change for the three sample trees. Elemental analysis of foliage did not reveal such a trend. There is no evidence of a common chemical factor which controls growth by

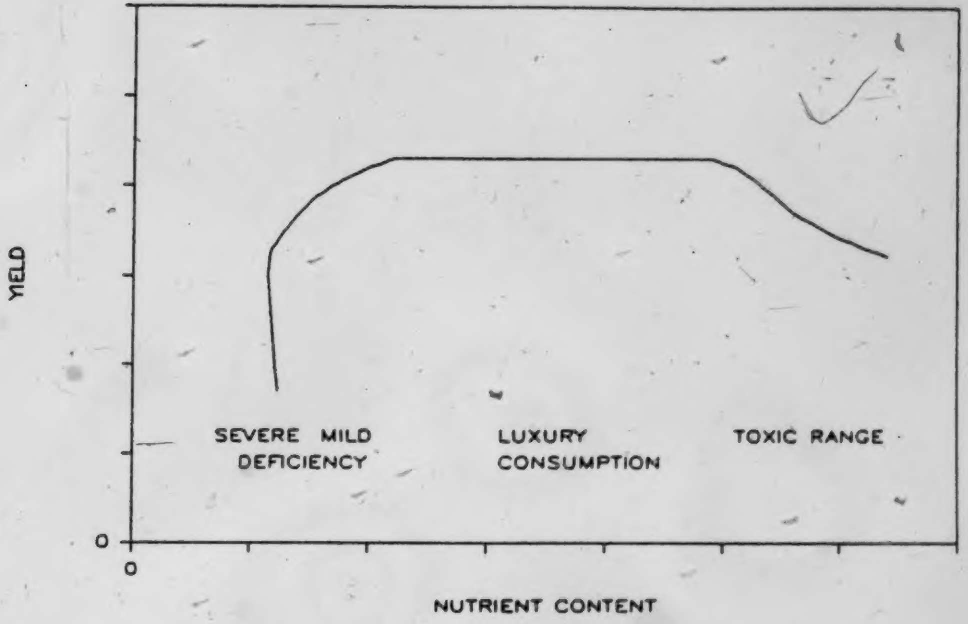

FIGURE 16. The generalized relationship between nutrient content of plant tissue and yield, showing the effects of deficient, adequate and toxic concentrations of a nutrient element on plant growth response (modified from Mengel and Kirkby, 1978)

TABLE 15. Elemental composition of plant tissue (mg/kg) determined by dry ashing.

	P (range)	K (range)	Ca (range)	Mg (range)
LEAVES				
A	1860 (1790-1930)	12760 (10463-14387)	9762 (9079-10187)	2284 (1777-3302)
BC	2157	18001 (16814-19189)	7704 (7443-7966)	1576 (1094-2059)
D	2056	14051 (11308-16795)	9582 (9229-9936)	2180 (1651-2710)
RECORDED VALUE*	1813 (1350-2500)	11742 (7900-18850)	11566 (8050-14800)	2526 (1750-3500)
PETIOLES				
A	653 (550-756)	6440 (5256-7625)	4849 (4826-4872)	2312 (2308-2317)
B	548	7602	5137	2397
C	402	7892	6758	2836
SAPWOOD				
A	39.9 (39.9-40.4)	740 (689-792)	711 (709-714)	428 (326-531)
BC	38.5	615	654	346
D	28.0	460	680	260
RECORDED VALUE*	163.6 (45-550)	949.4 (300-3350)	1272.2 (450-4900)	306 (100-900)

* Johnston and Bartos (1977)

TABLE 15 cont. Elemental composition of plant tissue (mg/kg) determined by dry ashing.

	Fe (range)	Mn (range)	Zn (range)	Cu (range)	Al (range)
LEAVES					
A	102.3 (85.5-115.2)	102.1 (80.9-115.9)	151.9 (145.8-159.3)	6.8 (5.5-7.8)	39.8 (33.0-45.9)
BC	109.5 (101.5-117.5)	69.0 (56.4-81.5)	134.6 (126.5-142.6)	5.4 (5.4-5.5)	52.4 (42.5-62.3)
D	124.8 (112.6-136.9)	176.2 (165.9-186.4)	129.8 (113.9-145.8)	4.8 (2.1-7.5)	58.6 (49.6-67.5)
RECORDED VALUE*	94.7 (51.5-172.5)	223.0** (32-373)	99.7 (60.0-180.0)	--	23.0** (19-130)
PETIOLES					
A	77.8 (69.5-85.9)	55.1 (51.2-59.0)	134.0 (130.8-137.1)	31.1 (25.1-37.2)	nd
B	72.6	51.4	189.0	23.3	nd
C	82.2	115.3	204.2	17.5	nd
SAPWOOD					
A	6.9 (5.3-8.5)	8.0 (6.3-9.6)	23.4 (21.7-25.2)	6.8 (6.2-7.3)	nd
BC	8.8	2.7	15.8	2.7	nd
D	7.6	7.2	18.8	7.2	nd
RECORDED VALUE*	30.9 (4.0-137.5)	--	15.3 (7.0-35.0)	--	--

* Johnston and Bartos (1977) (nd...not detectable)
** Timmer (1985)

degrees resulting in the gradual improvement in tree growth response in lower slope positions. For the major nutrient elements, foliar concentrations for samples from site BC represented the maximum (P, K) or minimum (Ca, Mg) value for the catena while foliar levels for sites A and D were intermediate. In general, foliar levels of most nutrients are within ranges published in the literature. Considering the nature of aspen regeneration, it is possible that interconnected root systems may translocate water and nutrients among trees in the clone, thereby obscuring the effects of local soil properties. In addition, total leaf area, rather than individual leaf nutrient content may have an influence on aspen productivity in these sites.

Phosphorous

P levels in the foliage are similar to the average value for 20 aspen trees determined by Johnston and Bartos (1977), with site A recording the lowest values for trees within the catena. There was no obvious trend in foliar P levels between sites. Hacskaylo (1969) reports levels of 0.14 % for eastern cottonwood growing in P depleted solutions. Timmer reports a range of foliar P concentration of 0.20 to 0.29 % for poplar clones grown in acidified soils. White and Carter (1968) suggest a critical level of 0.17 % for eastern cottonwood.

Petiole P levels decrease in lower slope positions. Since petioles are mainly structural and conductive tissue, P concentration may not be as critical for proper function of the tissue as it is for leaves. No data are available for comparison of P levels in petioles of aspen poplar. Sapwood analysed for P had lower values than recorded by Johnston and Bartos (1977). The decline in sapwood P concentration from site A to site D may reflect more efficient metabolic utilization of P, possibly resulting from increased demands placed on plant P reserves by more productive trees growing in lower slope positions.

Potassium

Foliar K levels are within the range of values reported by Johnston and Bartos (1977). The highest levels of K were found in leaves from site BC. High levels of K in midslope positions correspond with low Ca and Mg levels. K concentrations in leaf petioles are highest in lower slope positions. Sapwood K concentrations are within the range of values determined by Johnston and Bartos (1977). K levels are probably not limiting to growth in the study catena. Interpretation of high K levels in midslope positions will be considered in relation to elemental ratios.

Calcium

Ca levels are slightly lower than the average of values presented by Johnston and Bartos (1977). The levels obtained in the present study are also lower than those reported for aspen by Pastor and Bockheim (1984) and for poplar clones (Leech and Kim, 1981; Timmer, 1985) grown in greenhouse studies. Low foliar Ca levels are observed in site BC with higher levels in sites A and D. No critical level for Ca in aspen foliage has been established, however even the low concentrations found in samples from site BC are well above the level of 200 mg kg^{-1} recorded by Hacskaylo (1969) for eastern cottonwood (Populus deltoides) seedlings grown in Ca free nutrient solutions. Foliar analysis does not suggest that severe Ca deficiency is limiting to top growth of trees in site A. The Ca status of tree roots for the sample trees is not known. Levels of Ca in petioles are higher in lower slope positions while sapwood samples from lower slope positions have higher Ca levels than those from upper slope positions. Values for sapwood are slightly lower than the average reported by Johnston and Bartos (1977)

Magnesium

Foliar Mg levels follow the same trends as for Ca. No Mg deficiency is indicated by the data.

Fe, Mn, Zn, Cu, Al

Levels of Fe, Mn, Zn and Cu do not vary dramatically from values presented in the literature. Hacskaylo (1969) reports levels of 90, 49, 14 and 2 mg kg^{-1} respectively for Fe, Mn, Zn and Cu in eastern cottonwood trees grown in complete nutrient solutions. Nutrient deficiencies of trace metals are not common in acidic soils, although Fe deficiency can be induced by excesses of metallic ions competing for the same transport sites. Analysed levels of trace metals in foliage samples from the catena are not high enough to indicate toxic effects of any of these elements.

Al levels in foliage are slightly higher than those reported by Johnston and Bartos (1977). Foliar Al levels are not a reliable indicator of toxic effects, since Al is not mobile in plants. The increase in foliar Al levels from site A to site D suggests a response to increased transpiration in lower slope positions. Available Al is high in all soil profiles in the catena.

I.N.A.A. Analysis

Table 16 presents elemental concentrations obtained by I.N.A.A. for aspen leaves collected from the catena. Levels for Ca, Mn and Zn are close to the values obtained with the dry ashing technique. Large discrepancies in Al, Fe and Mg content between the two techniques are attributed to the proximity of these results to the I.N.A.A. detection limits for these elements.

Although soil levels of As are very high, foliar levels are less than 1 mg kg^{-1} and are unlikely to be toxic. No foliar level of As has been established as toxic to aspen. As is relatively unavailable for uptake in the strongly acid soils of this catena. Liming these soils, however may reduce As fixation and raise solution levels to potentially toxic levels.

TABLE 16. Elemental composition of aspen leaves (mg/kg) determined by I.N.A.A.

	A	BC	D
Al	200	300	300
As	<1.0	<1.0	<1.0
B	43	46	56
Ba	90	30	50
Br	12	19	50
Ca	9000	6000	8000
Ce	3	2	2
Cl	900	2200	900
Co	2.1	3.1	6.9
Cr	1	0.8	0.8
Cs	<0.2	<0.2	<0.2
Dy	<0.2	<0.2	<0.2
Eu	0.07	0.06	0.07
Fe	230	200	160
Hf	<0.2	<0.2	<0.2
I	<5.0	<5.0	<5.0
In	<0.2	<0.2	<0.2
La	3.1	0.1	0.2
Lu	0.02	0.02	0.01
Mg	1700	1000	1400
Mn	110	62	180
Mo	<2.0	<2.0	<2.0
Na	60	40	30
Nd	<3.0	<3.0	<3.0
Ni	<50	<50	<50
Rb	10	<10	10
Sb	<0.1	0.1	0.1
Sc	0.05	0.06	0.06
Se	<0.5	<0.5	<0.5
Sm	0.02	0.01	0.04
Sr	100	<100	<100
Ta	<0.5	<0.5	<0.5
Tb	<0.1	<0.1	<0.1
Th	3.1	2.6	2.5
Ti	<100	<100	<100
U	<0.1	<0.1	<0.1
V	<1.0	<1.0	1.0
W	<1.0	<1.0	<1.0
Yb	0.18	0.13	0.15
Zn	120	110	130

B levels in foliage are similar to levels considered adequate by Hacskaylo (1969) for eastern cottonwood and by Carter and Klinka (1986) for forest trees in British Columbia. Toxic effects of B are not indicated since foliar levels in site D are higher than in site A. High levels of total B in the Boundary soil are apparently not toxic to plants.

Tissue Ba levels are close to the I.N.A.A. detection limit and are not considered reliable for interpretation of trends.

The trend to increasing Br levels in lower slope positions is attributed to passive accumulation. Br is not a required plant nutrient, and concentration of this element reflects the differences in transpiration between upper and lower slope positions.

Foliar levels of Co are higher in site D. Leaf Co levels follow trends similar to Mn which is also concentrated in foliage from site D. Cobalt is transported in plants in the xylem (Mengel and Kirkby, 1978) and tissue levels reflect transpiration rates. Although total Co levels in the soil are very low, the levels of Co in leaves from all sites are within the intermediate region for vegetation reported by Vanselow (1966).

Foliar concentrations of the rare earth elements Ce, Dy, Eu, Lu, Nd, Sm and Tb, and La and Sc are within ranges determined by various authors and cited in Kabata-Pendias and Pendias (1984). An extremely wide variation of elemental concentration of these elements for many plant species is reported. Most of the foliar levels determined in this study are close to I.N.A.A. detection limits and are useful as average conditions for the Boundary soil, but not for determination of uptake trends for the various slope positions.

Th levels in foliage reflect the increase in total soil Th from site A to site D. Soluble Th is readily absorbed by plants (Kabata-Pendias and Pendias, 1984) Foliar levels of Th in this catena are much higher than the range of 0.001 - 0.2 mg kg^{-1} reported for plants by Bowen (1979).

Elemental Ratios

Elemental ratios provide insight into the interactions of the nutrient elements. Table 17 shows the ratios of major elements and includes ideal ratios determined for a poplar clone grown in a greenhouse (Kim and Leech, 1981) and ratios calculated for leaf nutrient concentrations determined by Timmer (1985) for poplar clones grown in acidified soils.

Elemental ratios determined in this study indicate a relationship between site BC and site D which is similar to values calculated by the author for hybrid poplars grown in soils acidified with sulfuric acid (Timmer, 1985). Hybrid poplars responded to soil acidification with decreased growth rates and with increases in foliar Al, Mn, P, K and Zn. In the present study, higher uptake of K and P relative to Ca and Mg is indicated by higher foliar K/Ca, P/Ca, K/Mg and P/Mg ratios for site BC compared to site D.

The dramatic differences in P/Al and Ca/Al ratios observed by Timmer (1985) are not observed for the sites from the catena, and the trend to increasing P/Al and Ca/Al ratios in upper slope positions is opposite to the trend for the study of hybrid poplars.

5.5 GREENHOUSE EXPERIMENT

The purpose of the greenhouse experiment was to determine the relative effects of chemical, physical and biological factors in the differential growth response observed between upper and lower slope positions. Since soil materials were ground and amended with sand, physical factors such as bulk density, moisture status and light intensity were constant for all treatments. Plant diseases and other biological factors were not observed to impact on plant growth in the greenhouse experiment, therefore differences in growth response between plants grown in soils from upper and lower slope positions are attributed to soil chemical factors.

5.5.1 WHEAT

Growth response of two wheat varieties is illustrated in Figure 17. Atlas, an Al tolerant variety consistently outperformed Scout in these acid soils. Both Atlas and Scout performed poorly in the subsoils from site A (A-sub treatment). For the surface soil

TABLE 17. Ratios of major element concentrations for aspen leaves from the catena compared with optimum values (Leech and Kim, 1981) for P. deltoides and values for a Populus clone affected by soil acidification (Timmer, 1985).

	SITE A	SITE BC	SITE D	Leech and Kim (1981)	Timmer (1985)	
					acidified	control
P/K	0.15	0.12	0.15	0.22	0.12	0.17
P/Ca	0.19	0.28	0.21	0.48	0.24	0.18
P/Mg	0.81	1.36	0.94	2.22	0.90	0.58
K/Ca	1.31	2.34	1.47	2.20	2.10	1.10
K/Mg	5.59	11.40	6.45	10.31	7.88	3.44
Ca/Mg	4.27	4.89	4.40	4.72	3.68	3.20
P/Al	29.3	24.9	21.2	N.D.	22.1	96.0
Ca/Al	245	147	164	N.D.	91	522

N.D...NOT DETERMINED

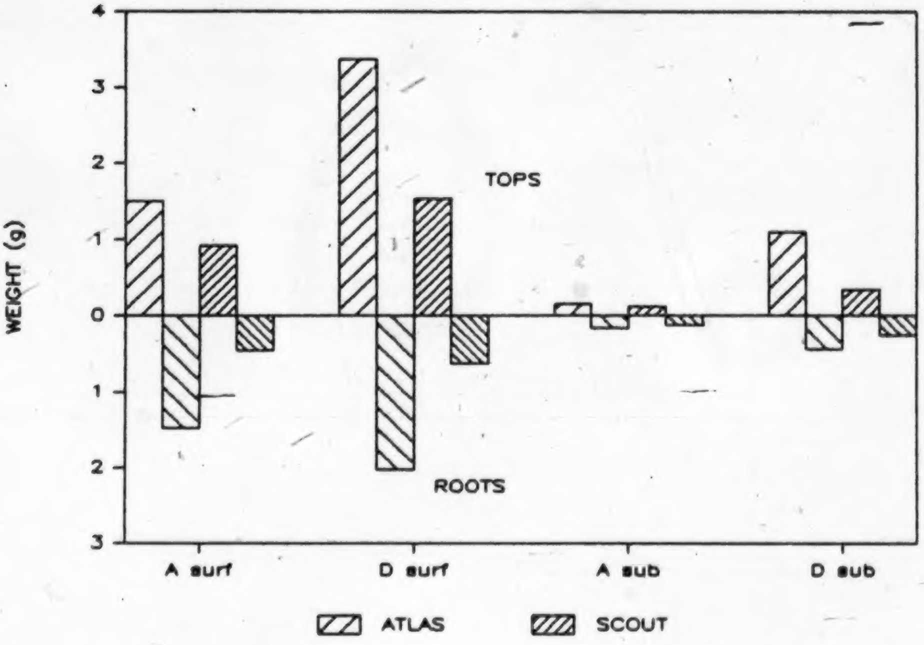

FIGURE 17. Growth response of wheat tops and roots in the greenhouse experiment. Differences in growth of Atlas and Scout varieties are attributed to differential tolerance to Al. Differences in growth response between treatments reflects the effects of soil chemical properties on plant growth.

treatments, Atlas displays a lower shoot/root ratio suggesting that improved root growth is associated with the improved performance observed for this variety. The Scout variety did not show obvious symptoms of growth restriction, yet was consistently outperformed by Atlas.

These results indicate that soil chemical properties play a role in growth response for wheat in these soils. Al toxicity is implicated as a causal agent since differences in growth response between these two varieties with differential Al tolerance was observed for all treatments. Observations of wheat roots indicated severe inhibition of root elongation and branching, and club shaped root tips for both varieties in the A-sub treatment. Root growth for Scout in subsoils from site D (D-sub treatment) showed reasonable root length but a lack of lateral branching and fine roots. Roots of Atlas in treatment D-sub showed good elongation and considerable development of lateral roots. The symptoms observed clearly indicate that root inhibition by toxic levels of Al and/or deficiencies of Ca is a factor limiting plant growth in these soils.

5.5.2 ASPEN

Figure 18 illustrates the growth response of aspen seedlings for the various soil treatments. For surface treatments, growth is considerably better in treatments C-surf and D-surf (surface samples from profiles C and D) compared with treatment A-surf (surface sample from site A). The best average growth was observed for treatment C-surf. Trees growing in treatment A-surf appeared healthy but were consistently smaller than those in the other surface treatments.

Root weights presented in Table 18 confirm that trends described for aspen shoots also pertain to root growth. Individual tree roots could not be separated and root weights are presented as totals for each pot. Symptoms of Al toxicity were observed on tree roots from the various treatments. Similar trends in the extent of toxicity to those observed for wheat are present for aspen trees from the various treatments. The data confirm that chemical factors play an important role in tree growth response in the greenhouse and suggest that the growth response of trees in the catena may also be partially attributed to soil chemical factors.

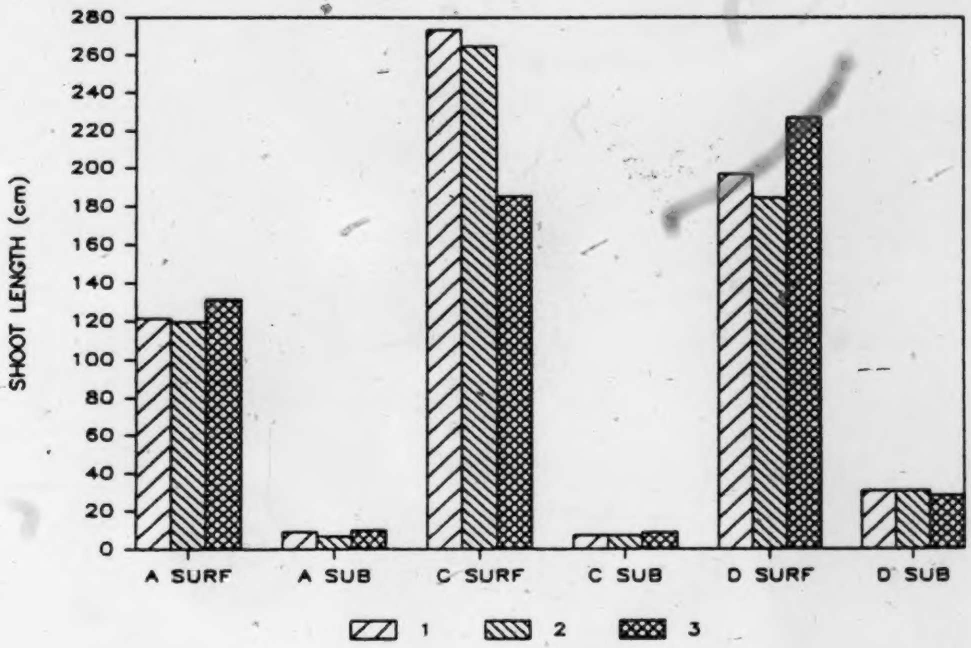

FIGURE 18. Growth response of aspen poplar in the greenhouse experiment. The values reflect average height growth for 3 seedlings from each of 3 pots (1, 2 and 3). Aspen growth for the various treatments in this experiment is similar to growth response observed in the catena for the corresponding slope positions.

TABLE 18. Aspen seedling root weight from greenhouse experiment.

TREATMENT	POT	WEIGHT (g)	TREATMENT	POT	WEIGHT (g)
A SURF	1	1.22	A SUB	1	nd
	2	1.00		2	0.02
	3	1.56		3	0.04
C SURF	1	3.48	C SUB	1	0.03
	2	4.09		2	0.05
	3	2.43		3	nd
D SURF	1	3.30	D SUB	1	0.25
	2	2.52		2	0.31
	3	3.65		3	0.15

nd...not detectable

Chemical factors such as exchange cations, exchange acidity and total N are very similar for surface soils from sites C and D. These factors suggest that growth response should be similar for the two treatments. Extractable P and organic carbon levels are somewhat higher for site D and would suggest a more favorable growth environment for treatment D. Trees from treatment C-surf, however, appeared to slightly outperform those from treatment D-surf. A closer relationship is observed between exchangeable Ca levels in the soil and growth response for surface soils, indicating that Ca is an important factor affecting tree growth.

Treatments A sub and C sub gave similar growth responses, which were poor compared to site D. This trend reflects many of the chemical properties of subsoil samples collected from the catena, such as exchangeable Ca and available P. While the applicability of results for this aspen seed source from Devon to the Boundary soil has not been confirmed, differences in growth response between sites C and D may be related to the effects of subsoil properties. Partial top dieback observed in site C may be related to nutrient imbalances associated with the vast discrepancies observed for the surface and subsoil treatments from this site.

6. DISCUSSION

6.1 CHARACTERISTICS OF THE CATENA

The catenary sequence is characterized by a number of physical and chemical gradients resulting from weathering of the shale parent materials and subsequent redistribution of weathering products. Topographic position in the landscape has strongly influenced the rate and direction of soil development in the Boundary complex, and steep topographic gradients result in a high degree of local variability in soil properties. The effects of topography as a soil forming factor are complemented by local hydrological and vegetation factors.

Illuviation is a dominant process of soil formation in the soils of the catena, and therefore they are classified as Gray Luvisols. The Boundary soil has many properties not normally associated with Luvisolic soils, however, owing to the nature of the pyritic shale parent materials. Characteristics such as extremely low pH and base saturation, high extractable Fe content, the presence of natrojarosite, unusually low Br, Ca, Co and Mn levels, and enrichment of As, Mo and V distinguish these soils from nearby Luvisols developed in other parent materials. Illuviation is accompanied by physical, chemical and biological processes of parent material alteration in the development of distinctive morphological and chemical characteristics of the Boundary soils.

Transport of illuvial clays results in strongly expressed Bt horizons in the profiles in upper slope positions of the catena. The accumulation of coarse textured glacial debris in lower slope positions is expressed as a lithological discontinuity and influences particle size distribution and soil chemical properties in these profiles.

Micromorphology of the profile from the top of the slope indicates a progressive alteration of the fragmic fabric type of the shale parent material to a granoidic - metafragmoidic fabric in the upper solum. Pawluk and Dudas (1978) attribute this transformation primarily to faunal reorganization of soil materials. In the profiles from the lower slope position granoidic - metafragmoidic porphyric fabric is observed in the lower solum while the upper solum is characterized by granoidic porphyric fabric. This transformation results from a coalescence of granic units caused by biological comminution and mixing of soil materials with organic matter. Thus a progressive transition is observed from the fragmic - fragmoidic to granoidic - metafragmoidic to granoidic - porphyric fabric, reflecting the degree of soil development in the Boundary soil. In these strongly acid soils, faunal activity appears to be the main agent of structural alteration, and a close association is observed between improved plant growth, depth of rooting and micromorphological characteristics.

Clay mineralogy is affected by pedo-environmental gradients within and between profiles. Mica, hydrous mica and kaolinite are present in approximately equal proportions. Alteration of clay minerals in the Boundary soil occurs as depotassification of mica. Mica depotassification has been observed for forested acid sulfate soils in Virginia (Singh et al., 1982). The degree of complete depotassification, as indicated by the intensity of 1.5 nm X-ray diffraction peaks, generally increases in the upper solum of all profiles and reaches a maximum in lower slope positions. There is little complete depotassification of mica below the solum. In general, acidity is thought to enhance mica depotassification. The extent of mica alteration in this catena, however is more closely associated with biological activity in the solum rather than chemical factors such as pH. The removal of K from the soil solution by plant uptake, and the subsequent shift in the stability of K bearing minerals in contact with the solution is a possible explanation for this observation.

The low pH values of the Boundary soils are attributed to the release of sulfuric acid during pyrite oxidation. Acidity of the catena soils is typical for inland acid sulfate soils in other areas of North America. Acidity decreases in the upper solum and this is attributed to the retention and cycling of plant nutrients in the upper solum. Higher pH values in the lower slope positions may be related to the influence of less acidic glacial materials in these profiles, to the leaching of excess acidity in these wetter areas and to more active nutrient cycling by the vegetation.

Transformations of Fe released from pyrite result in the dramatic color changes observed in profiles in upper slope positions, and account for the distribution of elements such as As, Co, Mn and V. The accumulation of secondary Fe oxides in the B horizon of profile A probably occurred in the early stages of soil genesis (Pawluk and Dudas, 1978). Soluble forms of Fe such as rozenite ($FeSO_4 \cdot 4H_2O$) which form quickly in exposed sulfidic materials (Wagner et al., 1982) could account for Fe mobilization and redistribution.

In profile A, hue changes from 5YR to 2.5Y across a sharp boundary at 43 cm depth. Similar transitions occur in profile B at 36 cm and profile C at 50 cm. A more gradual change in soil color is observed in profile D at 60 cm. The yellowish gray colors in the lower solum of all profiles reflect the presence of natrojarosite as a dominant Fe containing mineral. Redder surface horizons indicate the presence of goethite and possibly hematite. In surface horizons, D-C-B extractable Fe levels decrease in lower slope positions. D-C-B extractable Fe levels for the lower solum do not vary greatly throughout the catena. Total elemental analysis of Fe oxide veinlets and natrojarosite reveals enrichment of As and Mo, and depletion of Co and Mn in these materials. Veinlet samples were enriched in V while natrojarosite was depleted in this element.

Horizontal and vertical segregation of soil components results from a number of physical processes such as lessivage and erosion, and chemical processes such as release during mineral weathering, adsorption to surfaces, and precipitation. These factors determine particle size distribution, Fe transformations and the presence of natrojarosite, and the distribution of trace elements in the catena soils. Variation in soil properties such as pH, micromorphology, mineralogy and organic matter is closely associated with the extent of biological activity and the vigour of the forest community.

6.2 PLANT - SOIL INTERACTIONS

Variations in soil physical and chemical properties are closely associated with observed growth response of aspen poplar in the catena. Tree growth rates in lower slope positions appear to be typical for northern Alberta. The most important factors limiting tree growth in upper slope positions for these soils are water availability during periods of high transpiration (late summer) and inhibition of root growth by Al toxicity and Ca deficiency.

Measurement of soil water potential in August for upper slope positions indicated depletion to the 1500 kPa moisture tension in the rooting zone. Sucoff (1982) states that in controlled environment studies, transpiration rates for aspen poplar are reduced at leaf water potentials less than 1500 kPa. While the application of controlled environment studies to field situations has not been established, transpiration and photosynthesis may be restricted during this part of the growing season. Soil moisture depletion is exacerbated in this site by inhibited growth of sinker roots caused by Al toxicity, which prevents exploitation of subsoil moisture reserves. Observations of plant roots from the greenhouse experiment indicate that Al toxicity is a factor in growth response in the subsoils throughout the catena. Al toxicity is a debilitating problem in upper slope positions, while the effects are more insidious in lower slope positions.

The association of water stress and pathogen attack of aspen poplar is discussed by Sucoff (1982). Moisture stressed trees are most susceptible to attack by Hypoxylon canker. Infections observed in the catena were restricted to upper slope positions. The extent to which growth is affected by fungal pathogens is not known for this study.

The clonal habit of aspen poplar complicates the correlation of soil conditions with plant growth response. Interconnected root systems of aspen clones allow for exchange of water and nutrients among ramets within the same clone. Thus a particular ramet is only partially dependent on soil reserves in the immediate vicinity of it's root system for water and nutrients. This characteristic of aspen is a major adaptation which allows it to colonize harsh environments. Aspen is not well adapted to soil acidity (McCormick and Steiner, 1978) or to moisture stress (Sucoff, 1982), yet it is present in these locations where birch would appear to be better adapted. Root systems of aspen trees in the upper slope positions may be interconnected with healthier trees on the more hospitable north facing slope adjacent to the study catena, effectively enlarging their root system in areas where soil conditions are more favourable.

Results from the greenhouse study indicate that soil chemical factors also play a role in the observed differences in growth response in the catena. While leaf tissue analysis of trees from the catena did not reveal the presence of severe nutrient deficiencies or elemental toxicities, growth response for the greenhouse experiment is correlated with exchangeable Ca levels, indicating deficiency of this element may limit growth in upper slope positions. Foliar Ca levels in site BC were slightly below recorded levels in the literature. Slight dieback in midslope positions may be related to a deficiency of Ca. Other elements which were implicated in growth restrictions, such as P, K and Mo do not appear to be solely responsible for the observed growth differences. In these soils where P fixation would be expected to severely restrict P uptake, foliar analysis reveals P levels similar to average values for aspen growing in a number of locations (Johnston and Bartos, 1977). P levels are considerably below ideal levels determined by Leech and Kim (1981), for Populus deltoides clones growing in plantations. P deficiency may restrict growth in midslope positions as suggested by mild dieback of terminal leaders.

Total N levels for the catena reach a maximum in lower slope positions, but high organic C levels result in higher C / N ratios in these locations compared to the profiles in the upper slope positions. This suggests that the forest community in lower slope positions is more likely to be limited by N, since mineralization rates are usually inversely related to C / N ratios. Considering that trees are more productive in the lower slope positions, it is expected that there are greater demands for N in this location. The lower C / N ratios in upper slope positions suggests that trees growing in these soils are unable to fully exploit soil N reserves because of toxic factors or limitations imposed by deficiencies of other nutrients.

Toxicities of elements such as B, As and V, and many of the micronutrient metals and trace elements investigated do not appear to restrict growth in the catena, since tissue levels for most elements studied are within the range of normal values reported in the literature.

Results of this study illustrate the vigour of aspen poplar as a pioneer species. The ability of plant species to modify site conditions makes the study of plant - soil interactions a two way process, since simple cause-effect relationships are not always present in natural systems.

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